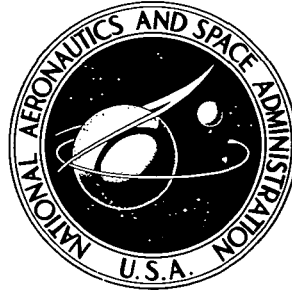


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ASTEROID AND COMET EXPLORATION

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16. Abstract <p>Exploration of Venus, Mars and the Moon have had two major scientific objectives. One was to clarify the processes which control planetary evolution. The fulfillment of this purpose, although far from complete, has been eminently successful in generating entirely new perspectives on the growth and differentiation of our planet.</p> <p>The second objective, particularly prominent in the planning of the lunar exploration, was to augment our understanding of the virtually unknown preplanetary history of our solar system. This would include the fundamental questions of the origin, emplacement and state of matter gathered around the Sun and some planets. Preplanetary history also inquires into the problems of fractionation, condensation, and non-gravitational aggregation of circumsolar and circumplanetary matter.</p> <p>Lunar exploration has provided some significant results relevant to these primordial objectives. Previously unknown or unclear effects of hypervelocity impact, aggregation in space of low velocity particles, irradiation of grains in space and surface reactions on the interface of solids with space were splendidly demonstrated in a well defined environment for the first time. However, apart from demonstrations of such processes, which must have been of crucial importance in the primordial era, no direct record was obtained from the time preceding the formation of the lunar crust. Hence the insights gleaned from the Moon stake out the realm of our most pronounced remaining ignorance - the earliest stages.</p> <p>Progressive track annealing, shock metamorphism, and melting and vaporization in the lunar soil and breccias indicate that impact velocities greater than a few hundred meters per second erase the pre-existing record in the projectile material. To have any chance to find primordial material that is not altered beyond recognition we must turn to bodies smaller than about a hundred kilometers, e.g., asteroids and comets. On such bodies material with low relative orbital velocity may accumulate without being destroyed. Furthermore, unlike</p>			
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massive planets, such small bodies will not destroy the original material by internal melting and differentiation.

Hence, in order to reconstruct the primeval history of the solar system we must apply the technological and scientific experience gained from the lunar missions to the exploration of the small bodies in the solar system. To the extent that these bodies have not been seriously altered by constructive and destructive collisions, comet and asteroid exploration holds promise for:

- 1) understanding the origin and early evolution of the building material of the solar system
- 2) clarifying the questions of growth and internal structure of massive satellites and planets
- 3) providing a record of the early history of the Sun, which is now an entirely speculative subject
- 4) possibly elucidating the mechanism of star formation.

The targets of immediate interest are:

- 1) asteroidal or extinct cometary bodies in near-Earth orbits (Apollo and Amor objects)
- 2) main belt asteroids with widely differing surface compositions
- 3) cometary structures and meteor streams
- 4) resonance bound objects in the orbits of the giant planets. Such bodies are possible remnants of the source material of the giant planets
- 5) satellites small enough to ensure preservation of their source material.

An appropriate exploration program would concurrently emphasize flight missions to comets and asteroids and intensified Earth-based and Earth-orbit studies of these bodies. A logical progression of flight missions would aim first at remote analyses by fast and slow fly-by, rendezvous and finally landings. In order to fully and accurately extract the wealth of information stored in extraterrestrial bodies, samples must eventually be collected and returned to Earth. The development of unmanned vehicles capable of such operation should be one of the primary goals of solar system exploration.

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ASTEROID AND COMET EXPLORATION

I. STRATEGY AND PROGRESSION OF EXPERIMENTS

The present knowledge of asteroids and comets has been extensively reviewed and extended during the last two years [1, 2, 3, 4]. This work has demonstrated that small and presumably primitive bodies may provide unique information necessary for understanding the formation and development of the solar system. This information may also be applicable to understanding the now commonly observed phenomenon of formation of dust envelopes around stars [5].

On the other hand, this evaluation has also shown how little is actually known about primitive bodies in the solar system and how interpretation of scanty experimental data rests critically on assumptions which are not yet experimentally verified. As a result, extremely different interpretations exist. Some of these appear to fit the total body of evidence more closely than others, and theoretical refinements can doubtlessly contribute further discrimination. However, there is a major need for actual measurements of the properties of asteroids, comets, and related objects before we can take full advantage of their potential for clarifying early evaluation of the solar system.

Although possibilities for further significant observation from Earth have not been exhausted, it is clear that the real breakthrough in understanding formation of matter around the Sun and the early stages of aggregation of solid bodies must come from space flight missions to asteroids and comets, first penetrating close to and then directly sampling these bodies. From a scientific point of view this direct sampling stage would be the most rewarding, hence the arrival at this stage should be accelerated in all possible ways. However, from the points of view of expediency, technological development, and most efficient planning for this ultimate stage, the logical progression would be to first carry out fast flyby and rendezvous missions before docking, local investigations, and sample return missions are attempted.

With this development in mind, a vigorous Earth-based observation program, that is supplemented with the new possibilities offered by Earth-orbiting laboratories; should be pursued; with inexpensive reconnaissance flights being prepared for early execution. These should be followed in the shortest possible time by sample return missions from easily accessible objects of prime scientific interest.

Detailed studies of the technical steps in such a progression are found in NASA documents listed in the references.

II. EARTH-BASED OBSERVATIONS

A. Spin State

The original spin state, including the rate and sense of rotation and the inclination of the spin axis of asteroids and planets, is a fundamental indicator of the relative roles of accretion and fragmentation in their collision history. In the case of the Earth, the original spin has been braked by the massive Moon; most satellite spins have also been tidally altered by the large central bodies. The original growth induced spin remains largely unperturbed in Jupiter, Saturn, Uranus, and most asteroids (Fig. 1). For those objects

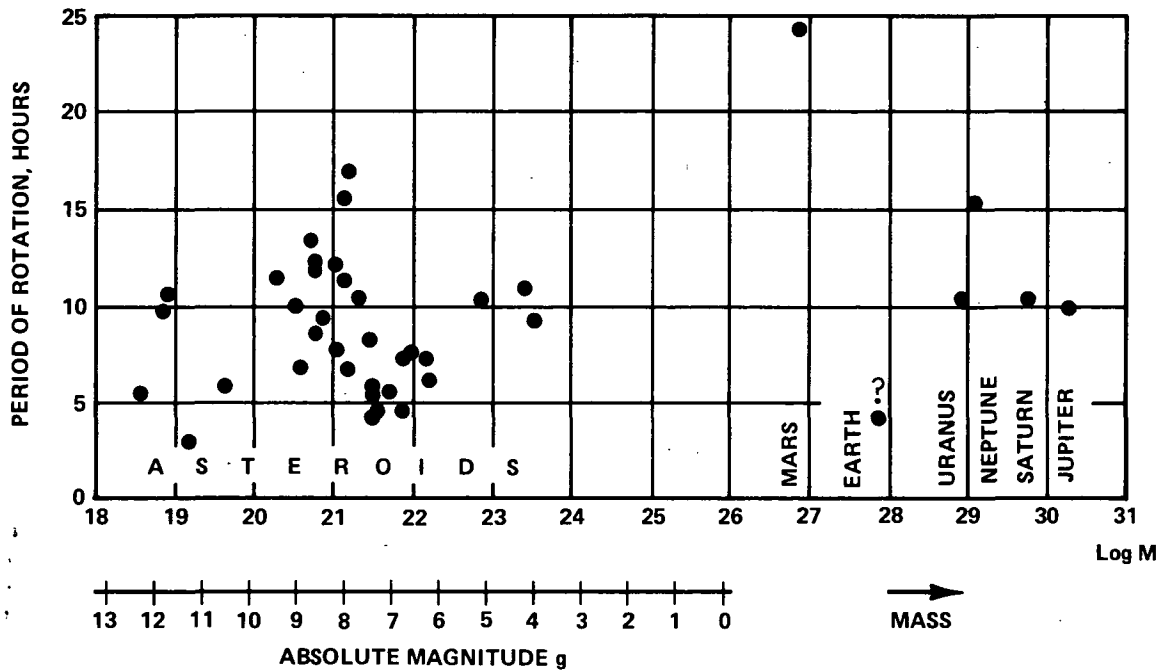


Figure 1. Periods of axial rotation for the asteroids and some of the planets in relation to their masses¹.

1. The period given for Earth refers to the spin before tidal braking [6].

which have distinctive marking or irregular shape, or which are accessible for radar measurements of the spin rate, this important property can be measured from Earth-based observations.

A traditional point of view, traceable to the early part of the last century, is that asteroids represent fragments from "explosion" or collisional breakup of the missing planet in the region between Mars and Jupiter. It has been shown [6, 7] that such a concept is untenable, in view of dynamic properties of the asteroids. It is furthermore an improbable assumption on the basis of any consistent theory about the formation of planetary bodies. In the light of such theory, it is more logical to assume that matter in the asteroid belt represents an incomplete state of accretion. The reason for the low accretion rate in the asteroidal region is the low concentration of matter there (lower by a factor of 10^3 and 10^5) compared to the adjacent Martian and Jovian regions respectively (Fig. 2).

Among the observations that force this conclusion is the distribution of spin periods among the asteroids (Fig. 1). If these bodies were predominantly produced by fragmentation at collision between larger bodies, the equipartition of rotational energy would require that on the average the less massive fragments should spin faster than the more massive ones. From Figure 1, it is clear that this is not the case; the spin periods are randomly scattered over a mass range of 10^5 among the asteroids, with an average of about 10 hours. As shown by Giuli [8], the spin state is controlled by the dynamical conditions for accretional growth of small bodies in Kepler orbits. This is further suggested by the fact that this mass independent distribution is characteristic, not only for the entire range of asteroids, but also for most planets.

This does not mean that collisions lack importance for the development of the asteroidal system. On the contrary, collisional processes must be a dominant mode for the exchange and dissipation of energy, and hence, for the dynamical evolution of orbiting many-body systems.

In order to evaluate the fine structure of the balance between accretion and fragmentation among the asteroids, continued and intensified measurement of the spin period distribution is of fundamental importance. Such measurements would also help in selecting specific objects as targets for space missions, and would also be of importance from the point of view of the technology of approach and landing.

Systematic measurements of spin periods have been pioneered by Gehrels and van Houten-Groeneveld and comprise 55 asteroids at the present

time [9, 10]. It would be of particular interest in the context of the space exploration to intensify these studies by securing information from: (1) all objects that are potential choices for missions, (2) as large a number as possible of members of individual asteroid streams, which stand in a particularly close relationship with one another, and (3) orbital regions (Psyche-Eleonora) where spin rate clustering is indicated [11].

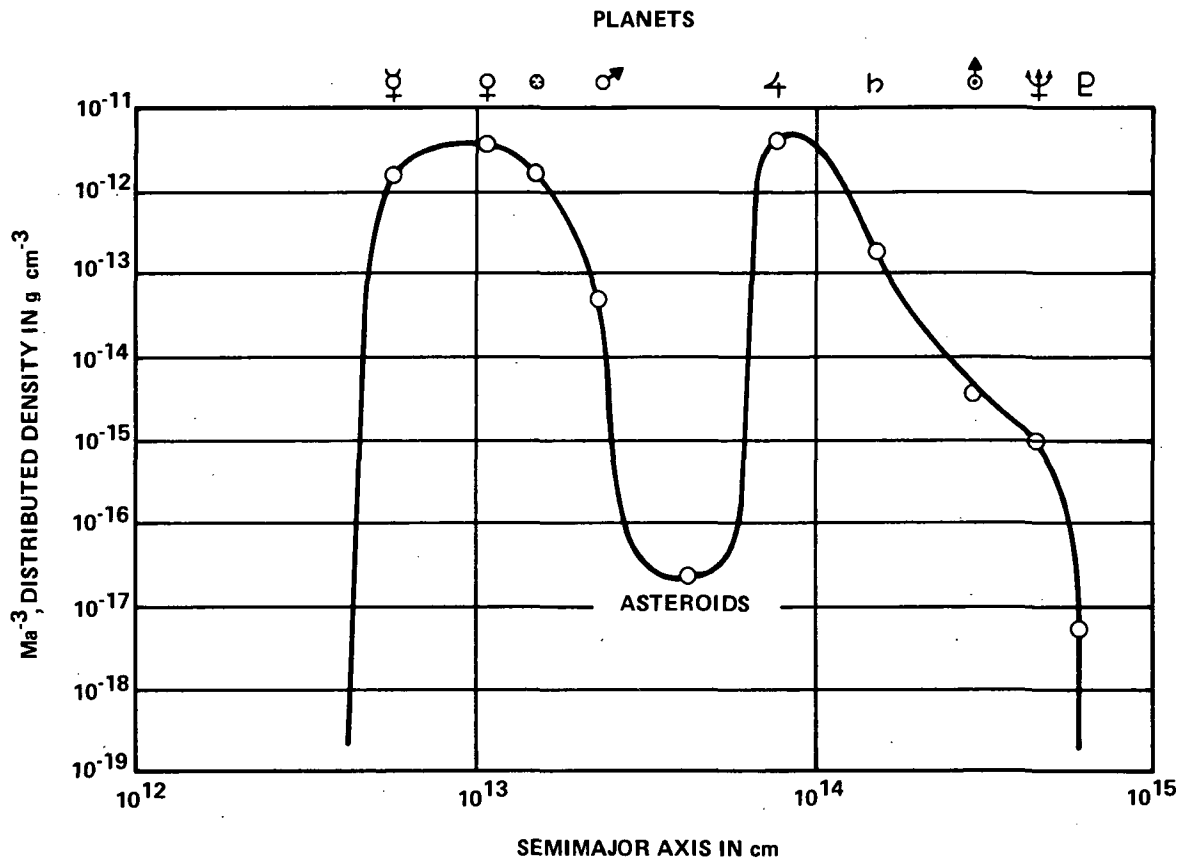


Figure 2. Distributed density versus semi-major axis for planets².

2. The distributed density is taken as the mass of the planet distributed over a toroidal volume around the present orbit; the small diameter of the torus is defined by the intermediate distances of adjacent planets. The distributed density, thus calculated, gives an over simplified picture of the primordial distribution of matter, which is, however, sufficient for the purpose of the present discussion. [4].

It has been clearly established in the 1970-1972 review of this subject, by the NASA Asteroid-Comet Panel, that to carry out such a program there is a critical need for a telescope dedicated solely to the purpose of asteroid-comet observations. Advanced plans for such a telescope facility already exist [12]. It would seem to be one of the most important immediate steps in planning for flight missions to asteroids and comets to construct such a facility and make it operative. The information return on such an investment would be exceptionally high, when the fundamental importance of the information and the need for space flight planning is set against the relatively low cost in terms of the space program.

B. Material Properties of Comets and Asteroids Evaluated from Earth-Based Observations

An Earth-based telescope, dedicated to the observation of asteroids and comets, would also have other important functions in evaluating the material properties of comets and asteroids, among them, a basis of selecting suitable targets for space missions. The work carried out even under the present relatively adverse conditions demonstrates that important preliminary information, which can serve as basis for distinct classification of the surface material of asteroids, can be attained by optical and infrared spectrometry and polarimetry. Furthermore, gathering of information on albedo distribution and shape, the latter particularly important in selecting targets for flight missions, are important tasks for an Earth-based observatory, dedicated to the planning and support of flight missions.

C. Orbital Dynamics and Resonance Studies

1. Near-Earth Objects. During a recent NASA sponsored study [13, 14, 15], it was discovered that four out of five analyzed near-Earth objects (Amor asteroids with perihelion distances between 1.0 and 1.38 AU and Apollo asteroids with perihelion distances less than or equal to 1.0 AU) are bound in various forms of resonance, either with the Earth alone or with Earth and Venus in alternation. This finding provides an important consideration in the selection of targets for asteroid missions. Previously, it was taken for granted that the asteroids were fragments of one or a few large bodies. It was also believed that the lifetime of the asteroids that penetrated into the inner part of the solar system would necessarily be small, because of the considerable risk of colliding with Earth, Mars, or Venus. Both of these considerations contributed to the relegation of the asteroids to a low level of interest.

The discovery that a large fraction of the Earth-approaching asteroids are bound to the inner planets in resonances raises the possibility that they may have persisted throughout a major part of the history of the solar system, perhaps extending into the formative era. If this can be proved, they will also become interesting in a new way; as they can be regarded as recording probes of the region of space where they are locked. The four asteroids so far found to be resonance bound are 1685 Toro, 1627 Ivar, 433 Eros, and 1221 Amor. Only one of the five bodies investigated, 1620 Geographos, was found to lack such a resonance connection.

2. The Lunar Evolution. The results from research on asteroidal orbits have a direct link with the question of the origin of the Moon, which has been brought into the foreground by the startling results of lunar exploration [16]. It is now commonly, although not exclusively, believed that the Moon originally was an independent planet, which early in the history of the solar system, was captured by the Earth (a similar development seems to have generated the pair Neptune-Triton). It is possible to understand the capture process dynamically as a result of a particular geometry of approach coupled with tidal exchange. However, if the orbit of the planet Moon was randomly related to that of the Earth, as previously believed to be the case with asteroids, it would be difficult to understand how this process could have any significant chance to occur. Although it is dynamically possible, the probability of a successful capture approach, as a single event in time, would be extremely small. However, if the Moon moved in an orbit coupled to the Earth by resonance, in the way now demonstrated for several asteroids, the opportunity would exist for approximately five hundred million interactive approaches before final capture. It has been suggested that this capture and the subsequent sweepup of the Earth's preexisting small satellites, are represented by the distribution of events existing in the lunar maria during the time period between 3 to 4 billion years ago [16].

The specific importance that consequently has become attached to resonance-bound bodies in the inner part of the solar system is one of several reasons to select such a body as the target for the first flight mission. Coupling of the practical considerations with scientific interest of this kind would make 433 Eros a target of prime interest.

3. Jovian Residues. There are several groups of well-known resonances in the solar system in addition to the ones mentioned above. One of them is the Trojans, objects locked in the Lagrangian points 60° preceding and following Jupiter. They are particularly interesting as possible remnants of the earthy and icy components of the original Jovian jet stream from which the

planet was formed. The Trojans are our best and probably only indicators of the embryonic state of an object retaining almost stellar properties. A detailed study of the Trojans could consequently cast badly needed experimental light on one of the most important problems of astrophysics - the process responsible for star formation. The present theories of this process are highly speculative, and the most common approach may be completely misleading.

The particular human interest in the past history of the Earth and our dependence on the terrestrial region in space, coupled with the practical considerations of accessibility, would favor selection of the Earth resonance-bound asteroids as targets of high priority in the early phases of exploration of primitive bodies in the solar system.

III. OBSERVATION FROM EARTH-ORBITING LABORATORIES

A. Unique Opportunities

The lifting of the restrictions imposed by the Earth's atmosphere will have important consequences for the analysis of asteroids and comets, as a step in the planning for flight missions. The fact that controlled observations outside the Earth's atmosphere will become possible during the early stages of comet-asteroid exploration should consequently be used to full advantage. The ultraviolet and infrared regions are of particular interest. The limited measurements of reflection spectra (color) which can be carried out from Earth have already shown a remarkable range of surface properties of asteroids [17].

In the case of comets, the information from ultraviolet line spectra has already begun to be exploited from orbiting satellites. Features that can be predicted can be checked by preset instrumentation relatively easily, without need for human feedback during flight. In this way it was possible to verify the prediction by Biermann of huge clouds of hydrogen emitting in Lyman alpha, around each of the three comets observed, including Comet Encke. The refined and versatile measurements, which will be made possible by a manned orbiting laboratory, will doubtlessly contribute further distinctive spectral features. Some of the important measurements require observation outside the geocorona.

B. Origin of Comets

Spectral observations that are free from atmospheric interference will be highly important for the evaluation of the fundamental question of the unknown source for the gas components surrounding comets.

In one widely accepted view, developed particularly by Whipple, these gases emanate from an icy conglomerate at the center of the comet, constituting a single solid core of substantial size. The gas emission in this model would also be responsible for the non-gravitational perturbations in the cometary orbits.

Other scientists [4] have drawn attention to the difficulties in reconciling this interpretation with a variety of different types of observations which indicate comets to be assemblages of loose grains. The gas emission in this model would essentially be the result of the release of volatiles at the collision of particles in the cometary jet stream. An objection to this view has been that such a gas source would appear insufficient to account for the gas fluxes estimated from spectral intensities, but this objection does not seem to be serious [18]. According to a recent development of this approach, comets may form as a meteor stream condensation produced by density waves which are excited by planetary perturbations [19]. Other attempts to account for the gas transport inferred in comets have led to the proposition of a compromise (icy halo model) between the two model types discussed above [20].

Regardless of whether comets are now dissolving to form the meteor streams with which they are often associated or if they represent progressive condensations of such disperse streams focused by planetary gravitation, it is necessary to assume that the latter process has been active in the past to generate any solid bodies that may exist in the nuclei today. The question is, whether today we do or do not still live in the era of comet formation.

As a different interpretation of the Lyman- α emission from comets, Lal proposed [21] thermalization and recombination of solar protons at collision with the cometary dust in the coma and tail, followed by diffusion and excitation of hydrogen in the observed Lyman- α halo. This view might seem to be contraindicated by the fact that roughly matching amounts of oxygen are deduced from observed OH emission. Most workers would take this as a support for the concept of water molecules as the source for both dissociated hydrogen and hydroxyl radicals.

These divergent ideas clearly point to the profitability of more refined measurements in the now largely inaccessible ranges of the cometary spectra, including the ultraviolet and infrared. In the case of comets, the potential of spectral information in infrared has been shown [22] by demonstration of the presence of the characteristic Si-O stretching band at $9\text{ }\mu\text{m}$, presumably to be the result of magnesium silicate components of the dust in comet Bennett.

C. Solid Objects

Also, the reflection spectra of asteroids offer interesting features from the ultraviolet through the visible region. The shape of the absorption spectrum in the ultraviolet region is a sensitive function of the content of transition elements in the surface material, particularly iron, and as such, is of diagnostic value.

The infrared measurements of asteroids have provided information on molecular vibration features, which are specific for different types of silicates present in the surface. So far, these measurements have been limited to the infrared windows in the Earth's atmosphere. Many of the distinctive features (discriminating between characteristic spectral features in different types of minerals) are located in the regions inaccessible from the Earth.

D. Circumstellar Envelopes

The ultimate aim of comet-asteroid exploration is the clarification of the original formation of solids around the Sun. Also here, infrared observations have given the first experimental evidence of the actual processes. These indicative observations come from infrared emitting stellar envelopes. These were first thought to be characteristic of T-Tauri stars but have now been discovered around stars of widely varying types. Again, the characteristic emission at $9\text{ }\mu\text{m}$ and another at $20\text{ }\mu\text{m}$ (Si-O₂ bending) suggest silicate grains as a ubiquitous component.

It is possible that we are dealing here with the same process of accumulation, ionization, and condensation of matter around a central body, which has led to the production of planets and satellites in our solar system in the distant past. The exploration of the unknown ranges of the ultraviolet and infrared emission from these possible nascent solar systems is another promising program for Earth orbiting observations, relevant in terms of solar system evolution and the formation of stars.

E. Instrumentation

The instrumental requirements for observations which are pertinent to the asteroidal problems include ultraviolet spectrometers, covering the range above approximately 2500 Å and capable of a resolution of about 200 Å. Since more stringent requirements are placed on cometary measurements in the UV region, both with regard to lower wavelength cutoff and to resolution, the requirements for asteroidal observation in this spectral range would not place constraints on the instrumentation.

In the infrared region it would be particularly important to cover those spectral ranges which are blanked out by the Earth's atmosphere. However, for comparison of spectral features, it would be most desirable to cover the entire infrared spectrum from 1 to 1000 μm, by several instruments, each one adapted to one spectral range.

IV. FLIGHT MISSION MODES

Flyby and rendezvous missions would be logical initial steps toward the final direct sampling of comets and asteroids. In the case of comets, such exploratory missions would be necessary in view of the almost complete lack of knowledge of the state of matter in their interior. In the case of the asteroids, such missions would be desirable for insuring proper design of docking, sampling, and analysis techniques. Flyby missions would be particularly useful if several objects could be incorporated in the same mission. Fast flyby would entail speeds of 5 to 12 km/sec for objects in low eccentric orbits, and up to 60 km/sec for objects in highly eccentric orbits, such as long period comets.

V. THE DIFFERENCE IN EXPLORATION APPROACH TO COMETS AND TO ASTEROIDS

From a scientific point of view, both comets and asteroids have important bearings on the same fundamental problem; namely, the formation of solid grains in the circumsolar region and the further evolution of primordial grains into larger bodies. However, the differences in the structural state of these two classes of bodies call for a difference in emphasis in the experimental approach during flight missions.

The problems which are particularly interesting in asteroid research have to do with the embryological aspects of planetology. This is due to several factors that contribute to destruction of the past record in larger bodies and may be absent in any but the largest asteroids. Although some highly significant facts can be obtained by remote observation, a dramatic increase of information on the recorded history will be derived from actual docking and sample return activities.

In contrast to objects classified as asteroids, both gas and solid matter are spread over a large volume of comets and the state of aggregation in their densest parts is highly uncertain. Before the problems that are relatively clearly outlined in the case of the asteroids can even be approached in comets, it will be necessary to establish by flyby and rendezvous missions what the size is, what the state of aggregation is, and what the dynamics are of any region of increased density which can be designated as a nucleus. This is regardless of whether the cometary nuclei are increasing in density or decaying, and regardless of whether they consist of particles without permanent contact with each other or contain one or more coherent solid aggregates.

In view of the disperse state of a significant fraction of matter in comets, much information on the composition and dynamical state of these particles can be gained from flyby missions. The large extent of the coma and tail regions makes it possible to integrate information over reasonable time intervals in fast flyby missions.

These differences make it desirable to define both the immediate goals of exploration and the measurement techniques, which are somewhat different for these two classes of bodies.

Under the term "asteroid", a number of objects are actually gathered of possible different origin. The main belt asteroids are probably planetary embryos retarded in their accretional development by the paucity of matter in this region of space. The Trojans are likely to be aggregates from residues of the Jovian jet stream. The near-Earth "asteroids" (Apollo and Amor group) are often thought to be extinct cometary condensates. From an exploration point of view, all of these bodies have in common a defined volume but lack extensive association with gas and dust. However, observations of transient atmospheric phenomena have been reported and some of the Apollo objects are believed to be associated with meteor streams. All of these objects are treated here under the general term "solid objects", differentiating them from comets and Lagrangian particle clouds.

VI. ASTEROIDS AND POSSIBLE LARGE SOLID OBJECTS IN COMETARY NUCLEI

A. Mass, Volume, and Density

Ceres and Vesta are the only asteroids which have been measured for mass and volume. Their densities are probably in the range of 4.5 - 5.5 g/cm³ [23], which gives some indication of a high content of nickel-iron metal (verifiable by radar measurements).

The bulk density of most meteoroids, impinging on Earth from space, ranges from less than 1 g/cm³ up to 8 g/cm³ (for iron meteorites). In principle, a given asteroid could have a density within this range.

Note that there is no stringent correlation between strength and density. A high strength and toughness is characteristic of the low-density portions of the meteorite Allende, with a porosity of around 25 percent. The high strength in this case is due to the thorough interlocking of twinned pyroxene crystals and other originally freely suspended components of irregular shape.

The density distribution in any individual asteroid would be of great value in reconstructing its formation and aggregation history. It would also give material characteristics important in connection with planning for docking and sample return. Since determination of density is possible in flyby and rendezvous modes, it should be considered one of the most important parameters to measure in early asteroid missions.

In view of the wide range of possible densities, even measurements with low accuracy, permitting a rough classification of the object, would be of value initially. The density estimates would be derived from measurements of shape, size, and mass.

The most promising methods for mass determination would be by Doppler tracking and by direct gravimetry. The former method would be particularly well suited for flyby and the latter would require an orbiting or hovering mode to permit a sufficiently close approach. With present Doppler tracking techniques, approach distances in the range of 1000 to 10,000 km would be required to attain 10 percent accuracy in mass determination of an asteroid with dimensions in the range of 25 to 45 km (Fig. 3) and with flyby velocities in the range of 5 to 10 km/sec. A closer approach, of the order of 100 km, coupled with slow flyby (order of 1 km/sec) would improve the accuracy of the mass determination to the range of a few percent.

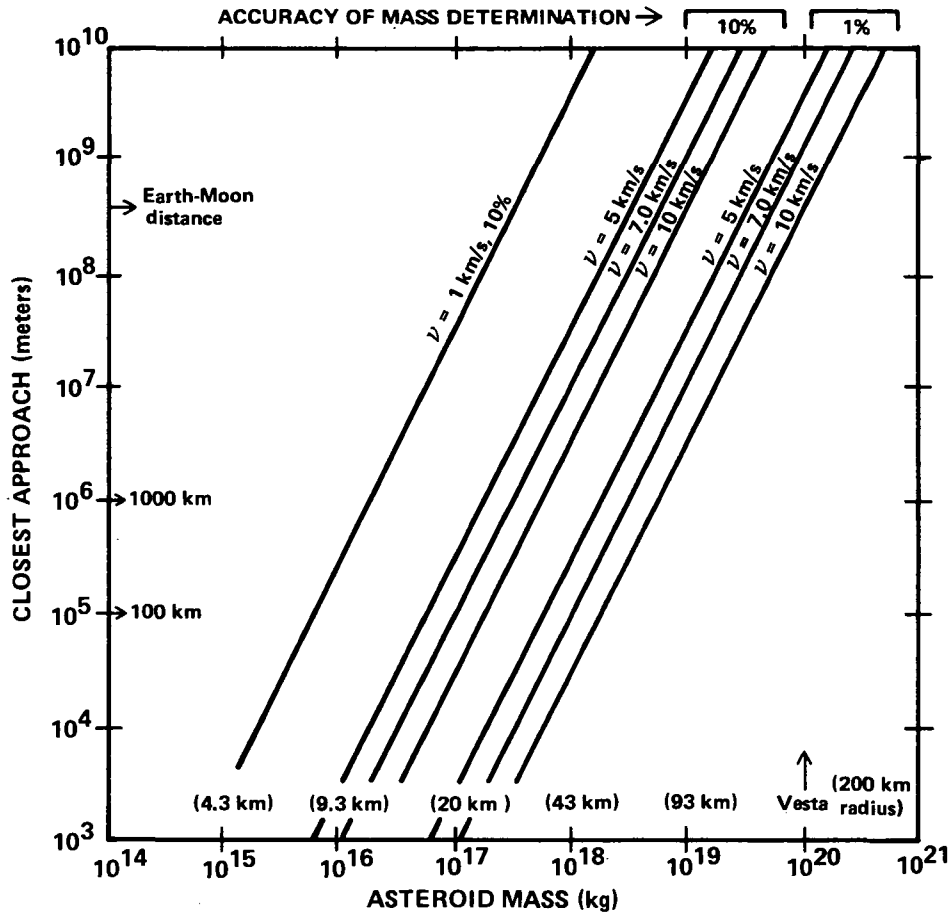


Figure 3. Possibilities of mass determination using flyby of an asteroid [12].

In the rendezvous mode it should be possible to measure total mass and mass distribution by gravity gradiometry [24]. The determination of inhomogeneities in the mass distribution made possible by this technique and by Doppler tracking in closed orbits around the object and at low altitude would open up another dimension in the understanding of the accretionary history of small bodies. This would be particularly so if, as suggested by radar measurements, metallic nickel-iron forms a substantial fraction of some asteroids. The size and distribution of individual bodies of metal in a body like an asteroid is a salient point in most of the discussions of the origin and the early heat structure of small bodies in the solar system.

Further refinement of gravity measurements by using gravity gradiometry should be made when docking and direct investigation of the asteroid surface can be achieved. Measurements on the asteroid surface would be particularly useful if they could be repeated at several locations. In the low gravity field of small bodies, ballistic transit from one station to another should be possible.

Early planning for gravity measurements in the proximity of and on the surface of the asteroids chosen as primary targets should be carried out. The various possible techniques should be evaluated with particular attention to the potential of Doppler tracking in fast and slow flying, and of gravity gradiometry in the rendezvous mode.

B. Shape and Size

Detailed shape information will be important for even relatively crude determinations, in view of the substantial deviations in some asteroids from the spherical shape that is indicated by light curve and radar measurements. Object shape and details of surface features are important for reconstructing the accretion and fragmentation history of the body.

From the crater density of the asteroid's surface, it should be possible to estimate, at least to an order of magnitude, the age of the most recent exposure of new surface by fracturing (in the same way as done for the Martian satellites). It should be possible from the shape of craters and surrounding regions to draw conclusions about the structure of the surface material and of the shallow interior of the body. The maximum size of craters observed will yield some information on the strength and cohesion of the bodies as a whole. (The first observations of small bodies in space, the Martian satellites, gave unexpected results in this respect.) It should be possible, particularly in conjunction with determination of mass distribution, to distinguish between irregular shapes caused by fragmentation and irregular shapes caused by agglomeration of a small number of bodies of similar size. This will ultimately lead to an estimate of the relative importance of fractionation and accretion.

Internal processes such as faulting, slumping, and collapse should be manifest in surface features observable from a distance.

Imaging of asteroids during flyby and rendezvous missions will make it possible to measure compositional heterogeneities suggested by albedo and color differences. Most importantly, the sense of rotation and inclination of

the spin axis can be determined. These two latter parameters give fundamental information on the accretion or fragmentation history in the same way as provided by an analysis of the spin rate (Section II-A). The former, in particular, offers greater determination difficulties from Earth based observatories. In an Earth based mode, it is impossible to determine the spin characteristics of isometric objects without substantial albedo variations, as such objects give rise to flat light curves without distinctive amplitude variations (Fig. 4). In view of the low gravitational fields of the smaller asteroids (which owe much of their scientific interest to their small size), terminal guidance would be considerably aided by imaging. As a result of the advanced state of this technique, this should not offer any difficulties in principle.

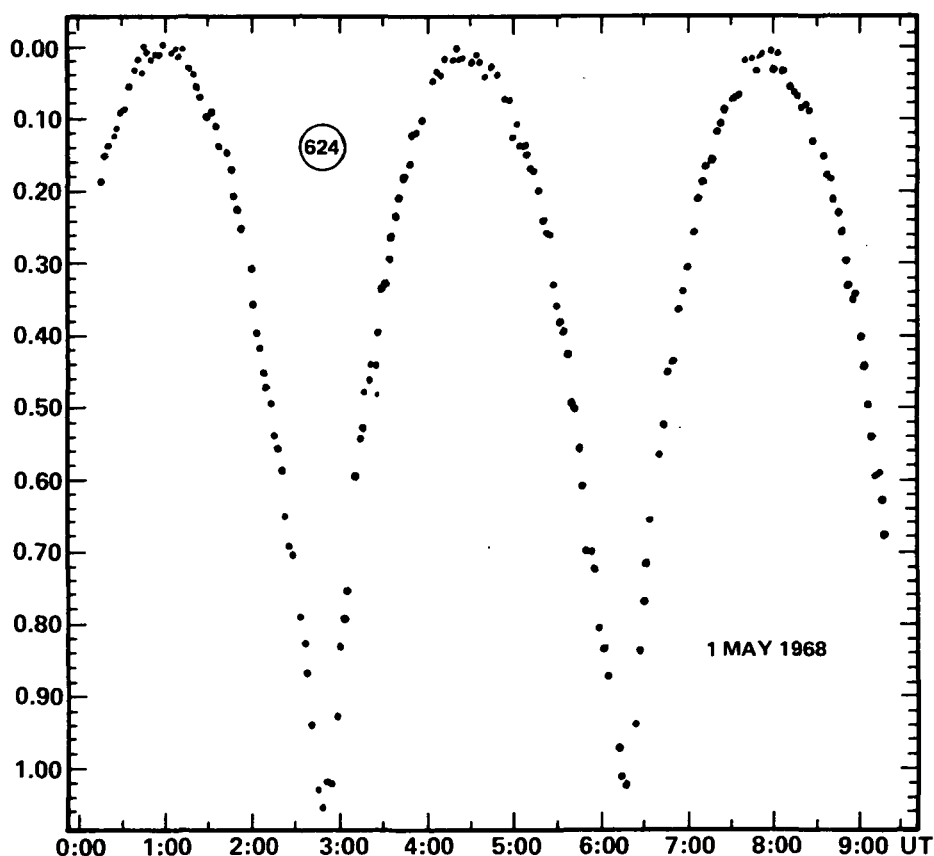


Figure 4. Lightcurve of asteroid 624 Hektor, a Trojan³.

3. The observations were made at the Cerro Tololo Observatory. As seen from the figure, Hektor has a rotation period of $6^{\text{h}}55^{\text{m}}$, with two maxima and two minima. The axis of rotation is nearly perpendicular to the line of sight [12].

The importance of imaging for maneuvering and terminal guidance, as well as for scientific purposes, makes the adaptation of suitable imaging systems a task of primary importance to asteroid and comet flyby and to rendezvous and docking missions. The choice of technique, spin scan or inertial pointing, should be evaluated for each application. The spin scan technique appears to offer attractive advantages in the flyby and rendezvous modes.

C. Magnetic Properties

Measurement of the magnetic properties of asteroids would provide information on the content and distribution of magnetic materials, primarily nickel-iron. The measurements of magnetic distribution would cast light on the important question of inhomogeneities in the asteroidal bodies; and hence, on the size and nature of the binding blocks. The significance of this question has been discussed in section B. A certain connection would be expected between density and magnetic phenomena, insofar as the highest density material that could be expected in this type of body would be nickel-iron. However, density also can be affected by compaction and by melting.

1. Iron Meteorites. Since nickel-iron is the component in solar system materials which gives rise to the most pronounced magnetic anomalies, we will discuss some of the possible modes of formation and significance of this metal. This question is important for clarifying whether the suggestion to use asteroid metal as a natural resource in the future deserves to be taken seriously.

The origin of the coherent bodies of metallic nickel-iron, that we know in the form of iron meteorites, is highly uncertain. In the oldest concept, associated with the idea of an exploded planet, iron meteorites were considered fragments of a once molten metallic core of that body. This idea had to be abandoned, not only for dynamical reasons, but also because the large spread in trace element composition of iron meteorites. These have proven to constitute a large number of individual reservoirs or chemical entities.

Another concept visualizes one or several hot bodies of asteroidal size made up of fine grained primordial condensate in the form of metal and silicate grains. Upon melting, the metal would be gathered into isolated clumps by capillary and possibly centrifugal forces. At breakup, by collision of the parent body, these clumps would be extracted as iron meteorites.

In a modification of this view, bodies accreted from original metal and silicate dust could become differentiated without melting. The rearrangement

of metal into bodies of the observed size of iron meteorites could take place by vapor transport, which becomes an effective process below the melting range of nickel-iron alloys.

In a third view, the aggregation of primordial grains of iron metal condensate could have taken place while these grains were still moving as individual particles in space. Below the Curie temperature, magnetic forces could have enhanced the cross section for accretion. The metal particle aggregates could have annealed together into large crystals of the high-temperature, face centered, cubic, gamma phase; either in the free state or during a prolonged period of slow cooling after the accreted iron lumps became embedded in the silicate material of growing embryos. Upon cooling through the region 600° to 400°C, these crystals would split up into the characteristic lamellar arrangement of alpha and gamma phase observed in iron meteorites. The substainment of the metal in this temperature range for sufficiently long time periods is assumed to have been possible by embedding the metal clumps into the interior of growing planetesimal embryos.

In the fourth concept, evenly distributed iron grains could have become melted originally by collisional impact between asteroidal size bodies. Then, melted iron again would be locally segregated by capillary forces from the silicate material. One could expect to find iron meteorites typically associated with melted and recrystallized silicate rocks of the type known as basaltic achondrites, which are very similar petrologically to the lunar basalts. Also, the lunar basalts could be regarded as examples of this type of segregation system, with the exception that in the high gravitational field of the Moon the metal would have drained down into the bottom of the melted pools.

The possibility that one could find an elongated body like Eros to consist entirely of nickel-iron has been suggested as an example of a possible trivial result of asteroid exploration. Contrarily, such a finding would indeed be of profound significance in view of the central role of metallic-iron bodies in the formation of the theories of condensation of matter and the subsequent growth of embryos in space, and the highly divergent interpretations of the samples of cosmic nickel-iron metal received on Earth. It would create great scientific interest to explore the internal structure of such a body; its surface characteristics, its original individuality in contrast to its derivation from a larger parent body, the evidence for fracture and deformation and their timing, the record of implanted gases, and many other properties which are particularly well recorded in metallic phases.

The discovery of a big body consisting of an alloy of a technologically highly important noble metal like nickel in the orbital energy vicinity of Earth would open interesting possibilities for its use as a natural resource at a future time when sufficient changes in momentum can be inexpensively achieved by nuclear rockets, or possibly by new types of space propulsion systems, drawing on ambient energy sources [25].

2. Exploration of Magnetic Properties. It would hardly be possible to obtain significant magnetic information, in the fast flyby mode and at large distances, since the small bodies in the solar system probably do not have dipole fields. However, in the rendezvous mode at low altitude, it should be possible to map any local magnetic anomalies, such as those found on the Moon.

Investigations on the asteroid surface after landing could give further detail and could establish a complete three dimensional picture of the fields. This is difficult on bodies like the Moon or the Earth because of their large radii; hence, the depth and shape of magnetic bodies in the interior of such bodies become largely a matter of conjecture.

Versatile magnetic measurement techniques have already been developed for space exploration. For the purposes discussed here, magnetometers operating at several sensitivity levels, such as those in the IMP, OGO, Mariner, and Pioneer instrumentation series would be useful.

Identification, measurement, and mapping of magnetized bodies in solid objects are of great scientific significance. They should be pursued by adaptation or modification of existing devices for instrument packages which can be used in rendezvous and landing missions, and possibly in slow flyby missions at low altitude.

D. Atmospheric Components and Dust

Since asteroids are too small to retain a permanent atmosphere, any gas concentration possibly found in their vicinity must be due to transient phenomena. One type of gas flux observed around the Moon is caused by the release of solar wind implanted gases from the saturated surface material. The measurement of this effect alone would not form sufficient justification for asteroid flyby or rendezvous experiments involving measurements of gas components. However, in multiple comet-asteroid slow flyby or rendezvous missions, when gas measurement capabilities are a fundamental aspect of the cometary experiments, observations near the asteroids could be included.

Another possible source of gas would be the decay of potassium bearing minerals generating argon-40 throughout the body of the asteroid. Furthermore, helium would evolve from the decay of the uranium and thorium series elements. Much smaller amounts of gases would be generated by the surface layer interacting with cosmic rays through spallation processes.

The fluxes of Ar-40 and He-4 would be of considerable interest for assessing the composition and porosity of these bodies. However, it is very unlikely that any of these fluxes could be determined through flyby or rendezvous measurements, and hence, like released solar wind implants, they will be important primarily in connection with landing missions.

1. Possible Relationships Between Asteroids and Comets. The suggestion has been made that some asteroids could be decayed, short-period comets and, in this case, that they could be sources of considerable gas flux. Candidates for such an origin would be the Apollo and Amor group of asteroids, because their orbital characteristics are more similar to those of short period comets than to those of the main belt asteroids. This is another reason for focusing early attention on the Apollo (perihelion ≤ 1.0 AU) and Amor (perihelion between 1.0 and 1.38 AU) asteroids.

Criteria can be established which would be suggestive of cometary origin of an asteroid. Such an origin could be considered possible, if the asteroid is found to consist of loosely consolidated material, with such properties that it could have harbored and interacted with volatile molecules. This could be responsible for the gas phenomena associated with active comets. If the asteroid still yielded a considerable amount of volatile molecules, particularly those observed in cometary atmospheres, a cometary association would be still more convincingly suggested. One possible and likely molecule of this kind would be water in the form of ice. A type of mineral association that could reasonably be suspected would be that of certain carbonaceous chondrites or gas rich meteorites.

Such findings would not be definite proof of a cometary origin of the body. It will simply suggest that it, or its building blocks, accreted and possibly spent a considerable part of its lifetime in the outer part of the solar system. On the basis of present knowledge, it would indeed be difficult to specify a criterion that would definitely prove that a body was of cometary origin, mainly because so little is known about comets.

Conversely, it is possible to specify the criteria which would disprove a direct cometary origin. If the body were a single fused or well annealed

mass of solids, without any significant porosity, this would remove the possibility for a reasonable source or reservoir of the gases observed in association with comets and counterindicate a cometary origin of the body.

Regardless of which set of current ideas is found to best describe the processes in the nuclei of comets, it is conceivable that relatively compact aggregates of earthy material could occur there. Such aggregates could possibly remain after substantial sublimation of the volatile components of original, large, icy conglomerate bodies. The residual material could then be held together by electrostatic forces, as found in the lunar soil [26, 27], or by hydrates and anhydrides left after evaporation of ice and clathrates.

Similar aggregates would, however, also be expected after perturbation bunching of particles moving in a cometary jet stream. Condensed cometary nuclear bodies would thus be expected, either as "extinct" residuum from dirty ice, or as primary products of meteor stream accretion. The latter mechanism must under any circumstances be invoked as a process in the past to explain any original formation of icy conglomerates.

Although the gas release phenomena in this degenerate stage have presumably become too faint to be observed visually from Earth, it is quite possible that during a long period they would be substantial enough to be easily measured in the vicinity of the asteroid. Considering this possibility, the measurement of gas components as well as the density, composition, and other properties of solid particles in the vicinity of such asteroids could be of importance.

If the asteroid were a senescent icy conglomerate, particle concentrations in its environment (such as meteor streams associated with Apollo asteroids, reported by Sekanina) would represent ejecta associated with the last stages of degassing. On the other hand, if it were a short period comet, where a residual asteroid is formed by the focusing of originally free particles and particle aggregates into a more or less dense aggregate, particle concentrations in the environment of the asteroid would represent the last stage in equalization of orbital energy between particles in this assemblage before they came at rest together.

Since these two situations should be distinguishable from a dynamic point of view by measuring velocity and direction of particles, measurements of both direction and velocity of particles in the vicinity of Apollo or Amor asteroids would be of great importance. Flight tested instrumentation capable of such measurements already exists (Sisyphus experiment).

Consideration of the direction and velocity of motion of small particles and comets in the environment of near-Earth objects forms an important link between comet and asteroid exploration.

2. Measurement of Gas Components. In view of the significance of the lack of gravitation in the source and flux of volatile components in loosely aggregated bodies, regardless whether they are of cometary or other origin, analysis of the gas and plasma components would be a task of major scientific importance in connection with landing on and sampling of such bodies. The emphasis on this type of investigation should be predicted by information obtained in flyby, and particularly in rendezvous missions.

At the present time, mass spectrometry is doubtlessly the best established method for identification and quantitative measurement of gas and plasma species. The use of electrostatic quadrupole, mass spectrometers permits the necessary resolution (better than one mass number) and the absence of magnets permits a low payload, which avoids the generation of interfering magnetic fields in the scientific instrument package.

Particularly in the flyby and in the rendezvous mode in cometary-asteroidal environments with low gas flux, the total concentration of gas places a limit on measurements. Integrating collection techniques have been proposed for such situations. This could be achieved by the condensation of gas and plasma components on a cooled probe, with subsequent release by heating of the total accumulated gas condensate into a mass spectrometer [28].

If an asteroid were found to consist largely of unmodified material, solids aggregated at low temperature, relatively high gas concentrations could be expected. The results from the Moon show that even at shock fusion of dust, much of the occluded gas is preserved because its escape is diffusion limited. Preferably, instrumentation for measurement of gas or ice on the surface of asteroids should be provided with collection devices or sensing probes that can penetrate into the subsurface layers. Any trapped or frozen gases could be released by heating and measured, in situ. For ice and water in other forms, thermal neutron absorption offers a sensitive and easily applicable technique.

3. Measurement of Solid Particles. Determination of the elemental composition of solid particles in the environment around asteroids by impact evaporation and mass spectrometry would be a way to approximately assess the chemical composition of the parent bodies, before landing was undertaken. However, impact evaporation-ionization becomes efficient only at fast flyby

velocities and the total intercepted mass is likely to be small. Emphasis should be placed on devices which make it possible not only to determine the impact frequency, particle mass, and composition; but also, if possible, the direction and velocity relative to the asteroid. From such measurements, one should be able to distinguish between the case of aggregation as a result of focusing of particles on the one hand, and that of gas propulsion of particles away from an icy aggregate exposed to the Sun on the other.

For the determination of the nature and origin of objects classed as asteroids, and their possible relation to comets, detection of significant amounts of gas or plasma in their immediate environment would be important. Measurement of velocity, direction, frequency, and mass of solid particles would also be desirable in order to determine if particles are being added to or removed from the body. Mass spectrometry of plasma generated by impact of solid particles should be attempted. For all asteroids, except those (if any) that consist of massive rock with negligible porosity, measurement of the gas flux from the interior by sampling after landing would be of importance. The mass range to be covered extends from 1 to about 300 atomic units.

E. Texture

The texture and state of cohesion of the material in asteroids, both at the microscopic and at the macroscopic level, would give important information on the evolution of these bodies. Accretion by collision of small particles with low relative velocities would result in a loose and porous texture with preservation of delicate crystal habits and of embrittled irradiation skins, such as found in carbonaceous chondrites and gas rich meteorites.

Aggregation of particles after collision at low relative velocities would be a prerequisite, at least for the initial growth of small bodies in space, since high velocity collisions between individual, free solid bodies are always found to lead to net loss of material from the target.

After initial growth by low energy particle collision and adhesion by electrostatic forces, the subsequent evolution of embryos could be complex. After the fluffy embryo has reached a critical size, interaction with high velocity particles can begin to lead to net growth also. This is because much of the energy of the projectiles would be dissipated inside the fluffy body and the resulting evaporation and ejected material from individual solid micro-particles would remain captured within the embryo. A body dominated by this process would be expected to assume a spongy, welded structure.

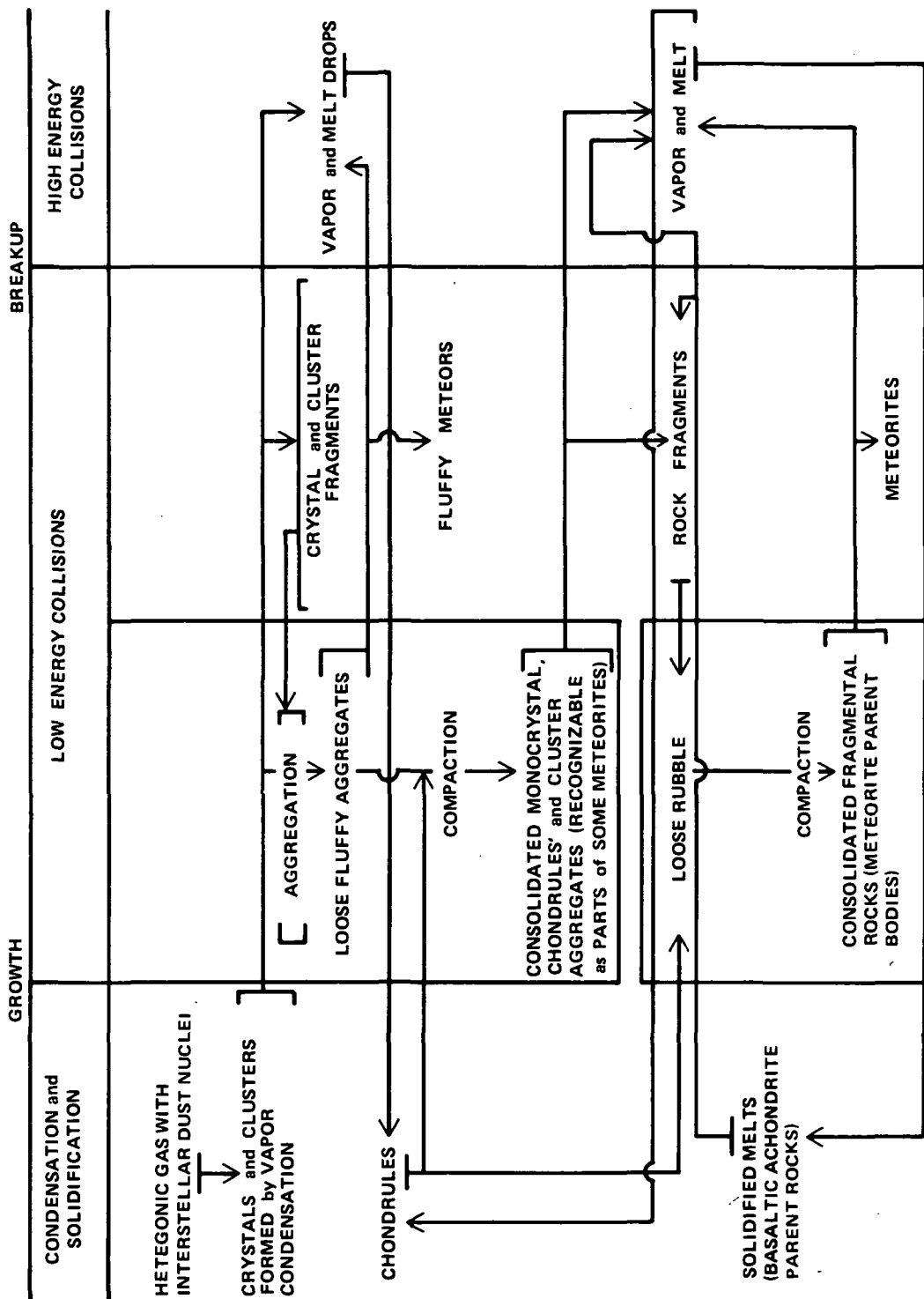


Figure 5. Development of small bodies.

Collisions of fluffy embryos with other such embryos at low relative velocities would lead to accretion without significant modification of the texture. At high relative velocities, such interactions would result in shock compaction and partial or complete melting together with generation of considerable amounts of melt and vapor ejecta.

The importance of such processes in the early history of the solar system is shown by the preponderance of chondrules as a major component of meteorites, furthermore by twisted and deformed fragments of nickel-iron metal, and solidified and fragmented melts (basaltic achondrites), which are similar petrologically to the lunar basalts. A schematic presentation of these collision interaction processes and the resulting products is given in Figure 5.

Heating due to radioactivity and other penetrating radiations would be expected to lead first to light and then to more extensive welding of grains into bodies of increasing rigidity. If a body like Eros were a primary embryo, not extensively modified by major collision breakup, one would expect the deep interior to be welded to some extent, and that the degree of sintering would decrease with distance from the center. The surface material would be relatively unmodified by sustained bulk heating. If, on the other hand, such an asteroid were a fragment of a larger body, this should be revealed in the corresponding variation in distribution of textural properties. The interior of the precursor body should in this case be exposed in part, and display the characteristics of more extensive sintering.

Presumably, hand in hand with textural modifications with depth would go changes in the state of aggregation of metallic iron. As discussed above, large vapor-grown bodies of metal could have developed to a greater extent at depth because heating could have been sustained for a longer time and higher temperature would have been reached. Iron oxide and finely dispersed nickel-iron metal would only be expected in the cooler surface layers, if internal heating has been substantial.

Since accretion and disruption presumably proceed concurrently in relative proportions, depending on the distribution of relative velocities of the colliding bodies, it is very likely that such breakup features would be observed in some instance. The information provided by the spin distribution (Section II-A) indicates that on a statistical basis the accretional processes must prevail over the disruptive ones, at least for bodies larger than about 3×10^{18} g. Consequently, one of the most important results of field studies of asteroids would be to give a quantitative and more detailed picture of the extent and manifestation of both of these processes.

1. Martian Satellites Compared to Asteroids. The Martian satellites are the only bodies near the same size as the asteroids which have been observed at a close distance. We should expect that some of their properties are characteristic of bodies of their size in general, and from studying them, perhaps we can draw some general conclusions about asteroids. This does not mean that the Martian satellites should be considered as captured asteroids, a suggestion which is unlikely to be correct for dynamic reasons.

Phobos and Deimos are observed to deviate from a spherical shape by not more than 20 percent; the impression of elongated bodies given by many photographs is due to the direction of observation relative to the solar direction (phase). Irregularities in the outline are seen which could be interpreted as breakoff of large fragments. They could equally well be due to irregularities caused by accretion of large individual lumps with the joints smoothed out by subsequent impacts. The visible surfaces of the Martian satellites appear to be completely saturated with impact craters, suggesting that shock induration may be a prevalent feature. The largest craters raise the interesting question of how Phobos could have withstood correspondingly large impacts without fragmenting. The answers to these questions probably lie in the texture-controlled response of these bodies. Their texture is unknown, and the raised crater rims bring up questions with regard to the response properties of the material. Raised crater rims on large bodies are mostly due to ejecta falling down near the impact site. On bodies with negligible gravitational field, this effect vanishes and the ejecta are sprayed out in space. Raised rims on such small bodies must consequently be due to ductility decompression rebound or puffing up of material after deep projectile penetration in fluffy material.

The surface of these satellites is completely covered with craters, and no unmodified surface is exposed. This demonstrates that no major collision breakup of these bodies has occurred, at least during a time long enough to collect so many impacts as to saturate the surface. This probably excludes a breakup later than at the earliest period of the solar system. The oblong shape (or heterogeneous albedo) of some asteroids, including Eros, raises the question of whether these features are due to breakup of a larger body or to accretion of a few embryos of large size. Also, albedo differences over the surface of more nearly spherical bodies may be responsible for the light variations generally interpreted as being caused by irregular shapes. As shown by Gehrels, polarization measurements may discriminate between these alternatives.

2. Asteroids with Non-Negligible Gravitational Field. The accretion behavior of the largest asteroids including Ceres, Pallas, and Vesta is atypical for the rest of the asteroids. The major scientific interest in the small

bodies comes from the fact that the original record would not have been extensively modified by either internal differentiation because of self gravitation and melting on a planetary scale, or by impact of gravitationally accelerated particles. No particles will, for example, hit Ceres (diameter 700 km) with velocity less than about 500 m/sec, which is comparable to the muzzle velocity of a high-power rifle. In the case of the small bodies (smaller than about 100 km) internal pressure is negligible and gravitational acceleration is tolerable (gravitational component of impact velocity ~ 15 m/sec for Eros). Hence, accreting particles have a finite probability to survive without structural changes and to contribute to the storage of data about their early history.

The largest asteroids with diameters of several hundred kilometers resemble the Moon with regard to material destruction. This places them in the category for further planetary exploration, but removes from the group of objects that are suitable for resolving the scientific problems tied to the very earliest processes in the solar system.

3. Measurement of Texture. The most promising methods for measuring textural properties are electromagnetic and acoustic sounding methods, of which the latter is only applicable in the landing mode. Electromagnetic sounding probably can not be applied with sufficient accuracy in the flyby mode. The rendezvous mode use of radar reflection has proven of value in the lunar exploration [29, 30, 31] and could be used to great advantage for probing of the surface and interior of asteroids and any large solid objects which might be encountered in cometary nuclei. The diffuse scattering of radar reflections on the Moon has caused some ambiguities in interpretation. As a preparation for design of instrumentation for asteroidal application, further theoretical work and experimental model studies would be desirable.

Electromagnetic sounding could give potentially important information on the physical state of the material in the interior of asteroids and solid cometary aggregates and also on the chemical composition, particularly with regard to the content of nickel-iron metal and of water ice, both of which dramatically affect the dielectric properties and electrical conductivity.

In the landing mode, seismic probing techniques would also provide means for assessing the internal structure. Again, the experience gained from Moon explorations demonstrates our lack of familiarity with the seismic behavior of bodies different from the Earth. Theoretical and experimental consideration should be given to the possible response of different asteroidal models.

Both active and passive seismic experiments should be undertaken. The passive experiments would be expected to reveal after-effects from active experiments or other external stress. If there are large and massive bodies in cometary nuclei, gas release from the interior and related collapse could possibly be traced by acoustic effects. However, discussion of surface experiments on massive bodies in comets is premature until their existence and gross characteristics have been established by flyby and rendezvous observations.

Electromagnetic sounding techniques which can be used in the rendezvous mode and after landing, as well as seismic techniques which can be applied on the asteroidal surfaces, would provide information of fundamental importance with regard to the origin and evolution of these bodies.

F. Chemical Composition

1. Comparison of Chemical Analysis in Flyby and Rendezvous, Landing Missions with Remote Analysis, and Sample Return Analysis. Measurements carried out after landing in direct contact with the surface, preferably by a mobile instrument package, permit a much higher sensitivity and resolution than remote measurement; and consequently, provide more significant information than the flyby and rendezvous modes can provide. But such analysis is far superseded by the sophistication that is possible in analysis of samples brought back to laboratories on Earth. The choice of analytical techniques and information to be emphasized when telemetering data back from asteroids (or from large cometary aggregates) and the choice of analytical approaches that should await the return of samples to Earth, are largely strategic questions.

The return of samples to Earth is such an obvious goal in view of the improved information yield, that all steps should be taken to achieve this as soon as one or a few primary targets have been selected and preliminarily explored. After an introductory rendezvous mission, this exploration can best be achieved by instrumented landing missions.

Another important aspect of long range asteroid, comet, and satellite exploration is the investigation of a large number of objects to obtain information about the diversity in chemical and nuclear composition of the solar system.

It is clear that only a limited number of the many thousand objects potentially within reach can be investigated by sample return in the next

decade, or subsequently, by manned landings. Also it is desirable to develop mobile, remote-controlled instrument packages that can be landed on such bodies and measure critical parameters with the necessary degree of precision at several locations and telemeter this data back.

2. Measurements in Flyby and Rendezvous Modes. Remote measurements of chemical composition in flyby missions can be achieved with present techniques only for a relatively small number of elements and with comparatively low sensitivity and precision, because of short integration time and small subtended angle. Nonetheless, such investigations would be important to indicate major characteristics of the composition of asteroids and objects in the interior of comets.

Differences in composition could be caused by three kinds of effects. One is characteristic for planets, including the Earth and probably the Moon, consisting of separation of light and heavy components in melt reservoirs. This is unlikely to have occurred on asteroids or on larger bodies broken up to yield asteroids, unless these parent bodies were very large, which is unlikely. The second effect, observed on the Moon and suggested in meteorites, consists in evaporative loss of volatile components at impact, or when subjected to bombardment by corpuscular radiation or electromagnetic radiative heating. The third kind of differentiation would have taken place in the partially ionized gas from which the solid materials form. There are indications in meteorites that such separation processes have been of considerable importance [32].

The measurements of color and albedo of a large number of asteroids suggest chemical differences in the surface material [17]. Hence, remote chemical analysis by X-ray fluorescence and gamma-ray spectrometry, which have proven eminently successful in lunar exploration [33, 34], would be a useful exploration tool for asteroids.

a. X-Ray Fluorescence. Analysis of characteristic X-rays from the lunar surface, excited by the Sun [35], has been developed into a versatile method for remote exploration [33] and was successfully applied during the Apollo 15 and 16 missions.

The technique relies on the fact that corpuscular and electromagnetic radiation emitted by the Sun excites the surface atoms of the objects irradiated in space, which subsequently emit their own characteristic X-ray recombination radiation. Because characteristic X-ray spectra contain very few lines and these are adequately resolved by modern energy dispersion techniques, this form of measurement has proven highly successful in the case of

the Moon and provides the most promising possibility for a complete mapping of the major characteristics of the chemical composition of the lunar surface.

A limitation of the method lies in the fact that only the major elements can be detected, and furthermore, the particularly simple K-spectra are excited efficiently by the Sun only up to about 2 keV. The range thus accessible includes essentially magnesium, aluminum, silicon and oxygen. Carbon could also be measured if it occurred in sufficiently high (but unlikely) concentrations; i. e., about 10 percent mass or more. The somewhat more complex L-spectra of the heaviest among the more abundant elements, iron and nickel, are also excited and are potential targets for analysis when further development of the instrumentation takes advantage of recent developments, particularly in the field of sensor techniques.

b. Sensing Devices. In the system used by Adler et al. [33], gas filled proportional counters were employed both for analysis of the fluorescent radiation from the lunar surface and for monitoring the intensity and spectral form of the exciting radiation from the Sun. This choice of counter was partly dictated by the state of the art when the design was frozen and partly by the weight limits precluding more than eight channels in the multi-channel analyzer, covering the range 0.75 to 2.75 keV. Future developments could avail themselves of important developments in energy discriminating solid state detectors, which now are used routinely for spectrometry in this wavelength range [38].

The application of crystal detectors to the present problem will have the advantages that (1) individual spectral lines can be recorded and integrated. This would make it possible to determine a larger number of elements than that possible with the filtering techniques used in present flight experiments. (2) The count rate and efficiency would be still higher than that possible with proportional counters, since the crystals are 100 percent efficient. (3) Measurements can be extended down into the 25 Å region, and could include oxygen and the L lines of iron and nickel. This would be in addition to the elements magnesium, aluminum, and silicon now detected by differential subtraction techniques. Figure 6 illustrates the separation of important lines. This figure assumes a state-of-the-art detector and electronics. It would be necessary to use special thin aluminum films (~ 1000 Å) on the detector face to prevent reflected sunlight from comets or asteroids from reaching the detector and generating a leakage current [36].

— Silicon detector, assuming
100 ev electronic noise
- - - Gas proportional detector

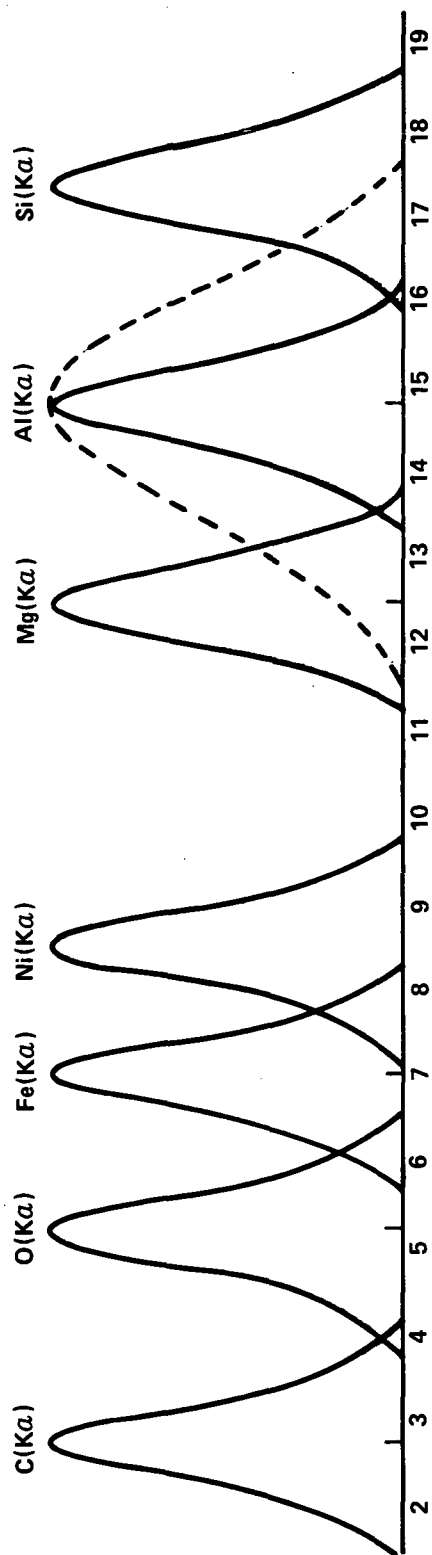


Figure 6. Calculated characteristic X-ray spectra - illustrating resolution of adjacent peaks.

Three practical complications are evident for employing solid-state devices. The first is the need to operate the detector and preamplifier at low temperature (100°K). Hence, the instrument package requires a coolant such as liquid nitrogen, or solid argon, or an arrangement for radiation cooling of these components in the spacecraft. Secondly, in making use of the ultimate resolution of the detector, vibration noise in the spacecraft during measurement must be minimized. Finally, to take full advantage of the large energy range of solid state detectors, a 512 channel analyzer is a minimum requirement; such analyzers have been flown as a part of the orbiting lunar gamma-ray experiment.

The dramatic development of solid state energy spectrometry in the X-ray region during the last ten years seems to be leveling off at the limit of what is now theoretically possible in this approach. New techniques with still higher sensitivity and resolution are in the offing, but have not yet reached a state of development that makes it possible to recommend them for flight applications at this time. Rapid advances could come about in this field, and in any planning for advanced-types of flight systems for the less immediate future, it would be worthwhile to consider such developments.

In contrast, the solid state detectors referred to above are fully developed on a practical basis so that they can be evaluated for immediate application.

c. Spatial Resolution. For the X-ray fluorescent instrument used during Apollo 15 and 16 missions, directionality and discrimination against background were obtained by the use of a collimator giving an effective solid viewing angle of 60 deg. At a distance of 111 km, the radiation analyzed would be derived from an area of 60 by 60 nautical miles. Under actual flight conditions, this area is stretched out in the direction of spacecraft motion to an extent that depends on the integration time. Under the conditions used in the lunar orbiting mode, 8 second integration intervals were used, resulting in the integration of emission from a strip of 60 by 120 nautical miles.

These properties of the system clearly put one of the more stringent limitations on its usefulness for comet and asteroid missions, where the total size of the total object is frequently of the order of magnitude of the area viewed from such a close distance as 100 km.

In a future design, it should be possible to improve this geometry considerably, by (a) decreasing the viewing angle through more stringent collimation and by (b) shortening the integration time. Both of these developments should be possible, since the actual count rates obtained during the

lunar orbital missions were many times higher than the necessary minimum signal to noise ratio. In view of the higher count rate of the proposed detector systems and the inherently better signal to noise ratio achieved through the covering of each spectral line and its adjacent background with many channels, it should consequently be possible to sacrifice count rate in the interest of spatial resolution.

d. Gamma-Ray Spectrometry in Flyby and Rendezvous Missions. The successful use of gamma-ray spectrometry for chemical mapping of the lunar surface from an orbiting station [34] has proven this to be one of the most versatile techniques for exploration in a remote sensing mode (the application of gamma-ray spectrometry for the landing missions and the significance of radiochemical information is discussed in Paragraph G-2 below).

Discrete spectral features in this range derive mainly from two sources: (1) decay of the natural radioactive elements uranium, thorium, and potassium and (2) gamma-emission induced by galactic cosmic rays and solar flare particles. In the latter category are neutron and proton induced prompt emissions from the major target elements, of which six were detected in the Apollo experiments. This also included gamma-decay of cosmic ray induced activities. Of fundamental importance in asteroid and comet exploration is the possibility for detection and measurement of water ice, hydroxyl silicates, and various hydrates by gamma-emission after thermal neutron capture by hydrogen. This possibility could not be used in the lunar experiment in view of the exceedingly low concentrations of hydrogen in most lunar surface material. They may be more abundant in asteroids, particularly at large solar distance. For highly eccentric asteroids penetrating into the inner part of the solar system and for less eccentric near-Earth objects, the abundance and depth distribution of ice could tell whether they have accreted in place or at larger solar distance. Also, how long they have been in their present vicinity of the Sun (Section II-C).

In the case of the comets, the presence, concentration, and state of distribution of water ice are likewise questions of fundamental importance in interpreting their origin and evolution, as discussed in Section II-C.

Flight tested gamma-ray spectrometric techniques are available and should be considered among the most promising tools for exploration in a rendezvous mission to an asteroid and to any solid object or gamma-ray dense clouds in the interior of comets. The applicability for a flyby mission needs to be evaluated in each case and depends on integration time allowed by relative velocity, distance, and size of the object.

3. Measurement Techniques After Landing. Chemical and isotopic information on volatile or easily volatilized components of asteroidal surface or subsurface material would best be provided for by mass spectrometry and possibly by infrared laser spectrometry, as discussed in the preceding topic.

For the bulk material which has low vapor pressure, various high energy spectrometric techniques provide the optimal combination of payload weight, simplicity of spectra, and range of coverage. These methods include: (1) alpha scattering, (2) excitation by various means of the inner level electrons and measurement of the recombination radiation, and (3) gamma-ray spectrometry.

a. Alpha Particle Scattering. This chemical technique has been perfected to a high degree by Turkevich and his collaborators, and has been proven in several unmanned lunar missions with impressive capability of prediction [37]. The method in its present form permits assay of the eight most abundant elements found in the lunar crust (> 0.3 percent atomic).

b. X-Ray Fluorescence. A great deal of preparatory work has been accomplished in this field by various agencies, however, the instrumentation has never been flown. The successful competition from the alpha particle scattering technique and the lack of development of energy spectrometry techniques in the decade preceding lunar exploration were probably the decisive factors preventing X-ray fluorescence from being used. The rapid development of energy discriminating solid state detectors during the last six years has dramatically changed this situation. It should now be possible to take full advantage of the possibilities offered by X-ray fluorescence, not only in the proven orbiting mode with solar excitation, but also for a large number of elements on the surface with artificial excitation sources. X-ray fluorescence techniques provide a valuable complement to alpha scattering, or possibly a substitute. Their yield is relatively low in the low atomic number range, where alpha scattering has superior sensitivity and increases in the higher atomic number range (at presently practical excitation voltages).

Particularly in the X-ray excitation source mode, X-ray fluorescence has superior sensitivity. The practical range can easily be extended to the order of 0.03 percent atomic as compared to about 0.3 percent atomic for alpha scattering. In a remote control mode, this practically excludes elements beyond the barium-cerium range from analysis by X-ray fluorescence. Aside from volatile elements above this range, such as mercury and the natural radioactive elements which can be assayed by nuclear spectroscopy, it appears most practical to reserve this part of the periodic system for investigations on

samples returned to Earth. If a need for analysis of some specific individual element or element group in this range is seen, it is possible that less general techniques with particular specificity can be applied or developed.

It is also possible to concentrate specific elements by fractionation, other than volatilization; i.e., by magnetic fractionation. However, none of these techniques are thought to give accurate enough results in the remote mode to be significant and should instead await application to returned samples.

(1) Excitation with electrons or electron excited X-rays. These methods have the advantage that a high flux and source brilliance can be obtained. The exciting beam can be shaped and the excitation source can be turned on or off at will. Hence, they do not constitute radiation disturbances interfering with other instruments or present a hazard at or before launch. Direct excitation with electrons offers the highest energy flux and relative simplicity; although, as an added minor complication, the accumulating charge has to be bled off from the sample target. Relatively high background due to scattering presents a drawback which limits the lower level for detectability of elements.

Excitation of the sample by the X-ray continuum from a high atomic number element target, such as gold or tungsten, offers the advantage of deeper penetration of the exciting radiation into the sample and low background scattering level. This permits an analysis in the 100 pulses per minute (ppm) range with integration times of the order of 10 minutes [38]. Sample charging presents no problem in this case. The L and M spectra of the elements used for excitation are superimposed on the sample spectra and consequently can cause interference. However, this problem is not serious because of the many choices of exciting radiation, and the possibility of switching electronically between them in the course of analysis.

All techniques using electronic excitation of X-ray spectra require a weight allowance for the high voltage generation equipment and other electronic circuitry. However, these components lend themselves to miniaturization. Typical total weights for portable equipment used on Earth is at the present time 6 kg. Also, X-ray tubes for this purpose have been miniaturized. Tubes with a typical rating of 50 kV at 1 mA, an X-ray flux of 10 Curie, and a weight of 300 g are within the present state of the art. Typical power consumption of the X-ray tube and the generator is 0.1 W at 50 percent electrical conversion efficiency.

(2) Excitation with a nuclear source. Excitation using a nuclear X-ray emitter has the advantage of compactness of the source and avoidance of malfunction due to failure of electronic components. However, it lacks the flexibility offered by direct or indirect electronic excitation. The intensities are relatively low, even at very high source activity levels in the Curie range, which pose a potential hazard in the case of damage on the ground. Shielding to protect against interference with other components of the instrument package is an added weight consideration, since the source cannot be turned off and on at will. The band fractions in the spectra blanked out by the source lines are generally considerably larger than in the case of electron excited X-ray sources. In the case of direct electron excitation of the sample, this problem does not exist.

The use of radioactive alpha emitters offers similar drawbacks but has the strategic advantage that such a source could also be used in alpha scattering measurements. Consequently, a possibility that should be seriously considered would be to expand the capability of the present alpha scattering instrument to include measurements on the simultaneously excited X-ray spectra by energy dispersion techniques. Promising studies in this direction have been made by Dr. A. Metzger at the Jet Propulsion Laboratory. The decisive question is whether sensitivities can be obtained that will be competitive with those obtained directly or indirectly from the electronically excited spectra.

An energy dispersion X-ray fluorescence system with a nuclear source has been developed for use in the Viking Mars landing mission [39]. It uses gas filled proportional counters as sensors; hence, resolution is considerably lower than that achievable with solid state detectors (Section VI-F, 2).

(3) Systems for X-ray energy dispersion and line detection. The failure of X-ray spectrometric techniques to make an impact on space exploration rests largely on the fact that at the time when these developments were undertaken spectral dispersion by crystals was the only practical method in this wavelength range. High resolution energy dispersion techniques were already underway, but the resolution was a function of energy and only satisfactory in the range of gamma rays. The development of crystal detectors with energy discrimination high enough to resolve the K lines of the spectra, even of the light elements, has revolutionized this field [38]. This has made it possible to make compact high sensitivity systems for remote control chemical analysis.

Energy dispersion techniques remove severe geometrical constraints that are typical of the optical geometry relied upon in wavelength spectrometry.

For example, one does not have to depend on the diffraction of the fluorescent radiation from the sample for analyzing crystals of different kinds, each one with its own detector. With a single energy resolving detector, the fluorescent radiation can be intercepted in a direction normal to the surface, where it is of highest intensity, and irregularities or variations in the distance to the sample surface are minimized as sources of error. As a result, it is possible with this technique to avoid any sample preparation or placement of the sample in accurately controlled geometry. Instead, the actual surface of the asteroid or cometary aggregate can be used directly as a sample.

c. Nuclear Spectroscopy. From a technical point of view, nuclear spectroscopic measurements which have proven highly successful in the lunar rendezvous mode [33, 34] are particularly attractive in the landing mode since no excitation of the sample is needed. Also, the emitted radiation is penetrating and when received from a large sample volume, it falls in an energy range which permits high resolution.

From a scientific point of view, the most important components of this type are potassium, thorium, and uranium. The ratio (K/U) has proven to be a parameter that varies strongly between different types of bodies in the solar system; hence, has diagnostic value. Furthermore, the absolute concentrations are of importance for the thermal evolution of the bodies in question, since these radionuclides are the most important long-term internal sources of heat.

In addition, there are possibilities for measuring gamma-ray spectra of a number of cosmic-ray induced nuclides. In themselves these would probably not justify measurement in this mode, but they provide valuable additional information that can be obtained with relative ease with the same instrumentation that measures the natural radioactive isotopes. Alpha and gamma spectrometric measurements of redistributed volatile radioactive decay products in the uranium and thorium series fall in this category.

4. Special Problems in Chemical Analysis.

a. Mercury. One component of specific interest is mercury which belongs to a group of elements with anomalous concentrations in meteorites (considering the amounts that would be expected if nuclide abundances were smooth functions of mass). On Earth it has been difficult to settle this problem satisfactorily since terrestrial contamination with mercury is sometimes invoked to explain such anomalies. In the solar system materials, mercury abundance and its variations are of fundamental importance since this element

is one of the relatively easy to measure indicators of fractionation in proto-planetary material [40, 41, 42]. The maximum level of mercury expected (in the 10 to 100 ppm range) would be on the borderline of what is practical by X-ray spectrometry; hence, if remote mercury analysis is desired, mass spectrometry or optical plasma spectroscopy must be used. Both techniques are developed at the level of compactness and ruggedness that make them suitable for adaption to space experiments.

Another concern arising from the cosmochemically important mercury concentration is that care should be taken not to introduce trace contaminants of this element in the asteroid or comet environment. From this point of view, it would be desirable to use cesium instead of mercury as an alternate fuel source for maneuvering near or on a sampling area for solar electric propulsion engines.

b. Water. Another component of key importance in judging the origin and the thermal history of asteroidal and cometary material is water, bound in the form of ice, hydroxyl ion, and water of crystallization. More or less direct evidence on this component could be obtained by mass spectrometry. However, when using mass spectrometry, a complication arises from the fact that in the preparatory process of ionization an uncontrollable fraction of the water molecules are ionized into hydrogen, hydroxyl, and oxygen ions. For this reason, it might be useful to consider indirect techniques such as the measurement of the change in the dielectric constant by adsorption of water molecules on aluminum oxide or other dielectrics. Such techniques have been under evaluation at the Jet Propulsion Laboratory and would be suited for rugged, simplified instrument packages without mass spectrometric equipment, as well as for in situ measurements on probes penetrating into the subsurface material. Absorption of thermal neutrons from an artificial source would be another simple and relatively specific method for measuring hydrogen. Detection of the emitted resonance line in the gamma spectrum would provide still higher precision.

c. Molecules Associated With Life Processes. Great scientific and humanistic interest would be attached to molecules associated with life processes and their occurrence in asteroidal and cometary material. As pointed out in NASA studies [12], comets and asteroids offer clues to the question of origin of life and the propagation of organic molecules through interstellar space that are unlikely to be obtained by observing the conditions on planets such as Mars.

On the other hand, a study of these compounds at the necessary level of sophistication is difficult, although not impossible to undertake in the field.

Again, here is a case where the greater ease and accuracy of analysis after return of the samples to Earth should influence the strategy. Attempts to measure in the remote mode require devotion of a substantial payload to the necessary instrumentation. Such instrumentation is relatively complex, yet does not have the flexibility, selectivity, or direct control sensitivity of laboratory techniques. Strategically, it would appear much more advantageous to achieve sample return to Earth within as short a time as possible and to apply the superior terrestrial sophistication to the study of this important problem.

In general, the art of sample return in unmanned missions is an important form of exploration where the U.S. space program is not yet at the forefront. The small bodies in the solar system offer the most inviting objects for early development and application of these techniques.

d. Radionuclides of Chronological Importance. Marginal approaches to age determination could in principle be attempted by remote instrumental analysis of the asteroidal surface material. The credibility of radiochronometric measurements, even on Earth, is highly dependent on the circumstances under which the analyses are carried out. Hence, if results obtained in a poorly controllable remote mode would indicate ages that were not considered surprising, the results would be regarded as trivial. If they were unusual, they would hardly be accepted before they could be verified by accurate investigation of returned samples.

The only type of measurement practicable at a reasonable cost would be the determination of gas retention ages, such as obtained from the ratio Ar-40/K-40. These could be of potential interest as indicators of the chronology of degassing events. However, the results from the Moon indicate that complications may arise from reimplantation of gas diffusing across the surface from the interior. For these reasons it would appear preferable to delay attempts at age determination until returned samples are available, hopefully, soon after the exploratory investigations by landing missions.

G. Crystal Structure and Phase Composition

1. General Significance. There is a multitude of possibilities for combining into actual molecular structures the elements that occur in phase sustaining concentrations in the solar system. The structures actually formed in a specific environment convey a great deal of information on the properties of this environment. Hence, if the structural properties of the material at a

molecular level can be determined, such investigations are obvious candidates for landing missions. The techniques to be considered are X-ray and electron diffraction, optical and infrared absorption, and polarization.

On the other hand, an assessment of the major phase composition at the level of sophistication required for discriminating conclusions is a task much more difficult than, for example, analysis for major chemical elements. Instrumentation suitable for flight missions does not exist, but several attempts have been made to initiate developments.

Analysis of phase structure should be placed in the category of measurements where cost efficiency considerations require that the ultimately necessary refinements should be carried out on samples returned to Earth. Again the importance of such investigations increases the urgency of such sample return. However, the relatively low resolution information that can be obtained in the remote mode could serve to answer questions of importance for target selection. It could also be useful for establishing large scale variations in composition of different asteroids and solid parts of cometary nuclei between each other, as well as local variations over the surface of individual bodies. For this reason, simplified modes of structural analysis would be useful and desirable for purposes of exploration. However, at the present state of the art it is not quite clear whether a significant resolution limit can be reached at a justifiable cost. Hence, this question has to be thoroughly investigated first.

2. Absorption and Polarization Characteristics. The application of optical techniques in the landing mode is largely limited by the fact that significant phases like sulfides, metals, and oxides are opaque in the optical region. Many of the components that are transparent in a pure and ordered state are rendered highly absorbing by impurity segregation, shock, and electrostatically induced adhesion of ultrafine particles which are characteristic of solids exposed in space [27]. Polarization measurements of unmounted samples in reflected or transmitted light give complex results. This is because of the combined effects on polarization (1) of total reflection at internal surfaces [43] and scattering at imperfections, (2) of reflection at external surface, (3) of texture effects caused by grains in the size range of the wavelength of light, and (4) (perhaps to the least extent) the factor of primary diagnostic importance, the anisotropy of the crystalline phases. Optical polarization phenomena which otherwise would be potentially useful in distinguishing between groups of phases would for these reasons be difficult to interpret in terms of phase composition.

Polarization measurements from Earth are nonetheless useful for remote characterization of the surface properties of asteroids, satellites and comets both in flyby and rendezvous (these applications are discussed in Section F-1.) For the reasons mentioned above, polarization measurements are less useful for close-up analysis in landing missions. Hence, they would not be immediate candidates for on-surface measurements.

In the 0.5 to 3 Å X-ray region, the typical penetration in silicates, sulfides, and metal phases is of the order of 5 to 50 μm . This represents a satisfactory sampling depth beyond the thin surface layer damaged by exposure to space radiation. The superior simplicity of the phase information obtained by X-ray diffraction makes this technique the major candidate for exploratory phase analysis. The choice of analytical radiation is dictated by penetration, resolution, and fluorescence caused by major chemical components of the sample with absorption edges near the energy of the analyzing radiation. Penetration becomes unsatisfactory for $K\alpha$ rays from sources consisting of elements lighter than vanadium or titanium, while resolution has the opposite behavior. Iron, titanium, and calcium in the sample are of major importance because they interfere with diffraction measurements by decreasing the signal-to-noise ratio resulting from fluorescence. Because resolution appears to be a significant instrumental limitation, relatively soft X-rays, such as $\text{MnK}\alpha$ or $\text{CrK}\alpha$, would be favored as exciting radiation.

3. Diffracted X-Ray Power. The diffracted power from specific sets of crystallographic planes depends largely on the degree of symmetry of the crystal, the degree of order, and the concentration of the phase. Among the minerals expected, metals and sulfides have high symmetry and resist dis-ordering processes. They can be determined even if they occur in relatively small concentrations.

Of the major silicates, pyroxenes and feldspars, in particular, have low symmetries and consequently give relatively low diffraction maxima and large numbers of lines to be resolved. The silicate structures are also conducive to shock disorder which lowers the diffraction intensity and broadens the lines.

Most carbonaceous materials, of the type known from space, have a low degree of short range order, and hence, would not be expected to fall at the level of practical determination by remote-control X-ray diffraction techniques.

The combined effect of these intensity determining factors makes it practical to analyze remotely only those phases which occur in concentrations

exceeding about 10 percent. In spite of this relatively low sensitivity, X-ray diffraction techniques can be useful for diagnostic tests involving major components.

The phases which would be most likely to occur in the accessible concentration range are the magnesium-iron silicates in the forms of olivine and pyroxene, metallic nickel-iron and iron sulfides, and possibly ice and inclusion compounds of ice.

It is likely that, at least in asteroids, impact shock as well as the rapid quenching of vapor clouds and melts have, in some instances, resulted in considerable amounts of silicates which lack short-range order, and therefore, do not give rise to distinct diffraction patterns. However, the diffuse scattering resulting from radial distribution of atoms gives rise to broad maxima, of which, at least the one corresponding to the Si-Si separation distance is generally strong enough to be discernible with the technique discussed here. The angular distribution of such diffuse scattering would automatically be recorded in diffraction experiments aiming at crystalline phases and could be used to estimate the proportion of vitreous materials.

4. Grain Size. The optimum crystallite size for securing satisfactory statistics by merging individual diffracted beams into continuous cones is about $2\ \mu\text{m}$. Acceptable results are generally obtained for grains from about 0.80 to $30\ \mu\text{m}$ diameter. The dusty appearance of asteroid surfaces, from telescopic polarization measurements, and the experience of such dusty materials from the Moon and from meteorites, suggest that a substantial fraction of the material would be within acceptable grain size range. Therefore, sample grinding would not be necessary, and X-ray diffraction intensity data can be converted, at least semiquantitatively, into phase concentrations.

5. Methods and Instrumentation for Measurement of Phase Structure and Concentration.

a. General Considerations. For reasons outlined in Section VI-G, 2, optical methods lack sufficient discrimination for phase analysis with unmanned instrumentation of the complex material expected. Furthermore, to extract a minimum of optical petrological information, it is necessary to mount the material to be investigated in a medium of comparable refractive index, bounded by optically plane surfaces. This type of procedure would be too complex to carry out by remote control in the vacuum of space.

X-ray diffraction techniques, which are the most promising, offer choices with regard to radiation source, sample geometry, and recording techniques.

b. Radiation Sources. The radiation source considerations are practically identical from a technical point of view, to those that have been discussed in Section VI-B. Considering all factors, electron beam excited metal target would be the most suitable choice for an X-ray source. Many features of such an excitation system are identical with those used in X-ray fluorescence analysis, which has been proposed as a suitable technique for elemental analysis. Hence, the development of a dual purpose source device should be considered.

c. Sample Geometry. Sample mounting could in principle be considered in transmission or reflection. Both types of mountings can be made with adhesive surfaces. Reflection samples can also be prepared without accurate control of thickness. They would consequently be simpler to prepare, particularly in para-focusing Seeman-Bohlin configuration.

d. Recording of Diffraction Effects. The fact that no X-ray diffraction instruments have been incorporated in flight instrumentation yet is due to the undeveloped state of electronic detection systems recording simultaneously along the arc of the diffraction circle. In the years preceding the Surveyor flights, several designs were considered using single gas filled detectors driven along the diffraction circle by a goniometer mechanism and recording one diffraction line at the time. It is clearly much more advantageous and less power consuming to arrange for simultaneous recording of all diffraction features. This can be done in several different ways.

One possibility is to use photographic film for recording, and to scan this film after development. This technique is used, apparently with success, in the USSR space program (although, as far as is known, not for diffraction purposes). The sensitivity is somewhat lower than that which is possible with electronic recording techniques, but the resolution is superior.

In electronic recording, it would be possible in principle to use a single proportional counter with the central wire laid out along the diffraction circle and discriminating with regard to position of signals along the wire. Such counters of linear type have been developed and described [44]. The difficulty in applying this technique to the present problem lies in the fact that the wire, in this case, cannot be kept straight but would have to conform to the diffraction circle. However, this would not appear to be excluded, and because of the simplicity of this potential technique, any planned development should seriously consider it.

The third alternative consists in using an array of a large number of independent detectors aligned along the diffraction circle. These detectors could either be individual wires in a single gas proportional counter enclosure,

or they could consist of a curved stack of individual crystal detectors. The former method has been proposed and made the object of a series of interesting developments [45]. The complication in this type of development lies in the large number of individual counter circuits needed. In the design proposed, 600 individual counting wires with separate circuits are included. However, this would not present an unsurmountable difficulty with the use of integrated circuitry.

The necessary memory system could be shared with other analyzing instrumentation such as the X-ray and gamma-ray spectrometers.

A fifth alternative, still further removed from the present state of the art, would consist in use of the fact that a dielectric scanning material along the diffraction circle accumulates local charge in response to irradiation by the diffracted beams. This charge can subsequently be read by scanning with an electron beam [44].

All of these alternatives share the possibility of using Seeman-Bohlin focusing geometry as proposed by Gregory and Parnell [45]. This has the added advantage that diffraction information is obtained from a relatively large sample surface and the diffracted beams are focused into sharp lines by virtue of the curvature of the sample.

Among existing instrumental techniques with practical potential, the one using the multiple wire approach is furthest developed, and hence, most promising for application. As the first step toward serious development of flight instrumentation, it would appear useful to make a careful experimental evaluation of all the detection methods discussed above.

The exploration of comets and asteroids should aim at returning samples from easily accessible objects of scientific interest as soon as possible by unmanned missions. When manned space exploration is resumed, asteroids of particular scientific or technological importance would be suitable targets. However, only a small number of objects can be thus investigated in detail. Partly for the purpose of preliminary exploration and partly to cover a large number of bodies of different type, it is important to develop instrument systems capable of measuring the elemental and phase composition of the surface material in several locations after landing. For such instrument systems electron or alpha particle excited X-ray spectrometry, in addition to α -scattering, should be considered for general purpose elemental analysis. The determination of chemical composition as a means for distinguishing materials of different origin is already a well proven technique in space, both

in rendezvous and unmanned landing mode. The determination of phase composition by X-ray diffraction analysis would also be a highly useful exploration technique with significant bearing on the origin and evolution of materials analyzed. It can only be applied in landing mode. Promising conceptual designs for instrumentation exist, but considerable development effort is necessary. If successful, such X-ray diffraction systems should be integrated in the instrument package of asteroid probes, if possible, by sharing X-ray source and multichannel analysis components with X-ray and gamma-ray spectrometers. Phase analysis by X-ray diffraction could also be applied advantageously to the exploration of comets, if sufficiently large solid aggregates are found in their nuclei.

VII. COMETS – SPECIAL CONSIDERATIONS

A. Nuclear Objects

As pointed out in Section VI-G, a main difference between the strategy for comet exploration and for asteroid exploration is that the nature and state of aggregation of the condensed material in the center of the comet is virtually unknown; whereas, specific techniques and operational modes for asteroids can at least be tentatively suggested at the present time. Consequently, with regard to the cometary nuclei, the most significant recommendation that can be made at the present time is to establish their approximate nature in flyby and rendezvous experiments.

The same observational techniques can be used for this purpose, as have been discussed for asteroids in Section II, with particular emphasis on the volatile components, as already indicated (Section VI-D). If such investigations demonstrate the existence of one or more coherent solid bodies, large enough for docking, the same procedures could be followed as suggested for analysis of asteroidal surfaces after landing. The particular aspects that would be of importance in the investigation of such cometary aggregates have been discussed in each of the pertinent paragraphs dealing with asteroidal analysis above. There is, however, not much point in specifying procedures in detail until the first observations of these objects have been made.

One of the major aims of the early flyby and rendezvous missions to comets would be to provide sufficient resolution for detection and imaging of nuclear objects, regardless of their size and state of dispersion. If cometary bodies are found that are sufficiently large for docking, their physical and chemical properties could be investigated by the same techniques as outlined for asteroids.

B. Cometary Envelopes

In the case of comets, special considerations also arise from the fact that they are an intermittent source of plasma, and that this plasma can serve to probe the interplanetary magnetic field and the solar wind. This is an added attraction in physical studies of comets, indirectly related to the major reason for interest in the small bodies, namely their potential information on the earliest history of the solar system which is obliterated or inaccessible elsewhere.

In this context, we need not comment on the techniques for exploration of the cometary plasma since much of the necessary instrumentation has already been developed and used in the Earth's magnetosphere and for interplanetary probes. Measurements of this kind would be a most important aspect, particularly in flyby and rendezvous missions of which both instrumentation and procedure have been discussed extensively elsewhere.

A point that should be emphasized here is that the cometary environment illustrates particularly well the homogeneous distribution of particles and fields in space, which is also demonstrated in the solar corona and in the Earth's magnetosphere. This should be taken into account in the design of cometary plasma experiments, which would emphasize short integration times permitting resolution of individual plasma filaments and sheets.

VIII. SELECTION OF TARGETS AND PROSPECTIVE MISSIONS

A. General Considerations

The main factors to be taken into account in determining target priorities for comet and asteroid missions can be summarized as follows:

1. Scientific considerations
 - a. Physical and chemical characteristics of primordial matter; nucleation and condensation of matter in space with application to similar processes around stars
 - b. Processes of accretion and disruption of bodies with negligible gravitational fields, including planetary embryos

- c. Progressive alteration of primordial matter
 - d. Origin and evolution of Earth, Moon, and the terrestrial region of space
 - e. Record of solar evolution, with application to evolution of stars
 - f. Nature and aggregation of matter at large solar distances
 - g. Process of formation of regular satellite systems
2. Accessibility and economy
 - a. Distance from Earth
 - b. Differential orbital energy and angular momentum
 - c. Size and complexity of payload
 - d. Launch opportunity dates
 3. Multiplicity of targets
 - a. Several asteroids
 - b. One or more asteroids and a comet
 - c. Comet in combination with other space probe experiment (Helios)
 4. Technological considerations
 - a. Near-Earth asteroids as instrument bases
 - b. Near-Earth asteroids as potential sources of material of technological interest; e.g., nickel-iron

The scientific criteria for selection of asteroids have been discussed in detail above. Many of the arguments contribute to making the resonance bound asteroids in the vicinity to the Earth, particularly Eros, obvious targets for early rendezvous missions since they combine all of the criteria of scientific considerations (1) and accessibility and economy (2) and have potential interest under technological considerations (4).

With regard to the nature and aggregation of matter at large solar distances (1f), it would be important to select for exploration both comets with highly eccentric orbits reaching far out into interstellar space, and short period comets, possibly forming transition cases to the near-Earth asteroids. Furthermore, the comets selected for study should preferably display the characteristics that give rise to differences in interpretation, such as irregularities in apparition, variability in appearance of nuclei, difference in dustiness, and coherence of associated meteor streams [46]. From this point of view, the majority of comets appear eligible. Emphasis can hence be placed on accessibility and economy (2) and multiplicity of targets (3) in the case of flyby and rendezvous missions.

Particular attention has been given in the literature to Comet Halley as a suitable long period comet and Comet Encke as a short period comet fulfilling the requirements outlined above. A particularly suitable target for a single comet mission, emphasizing accessibility and economy (point 2), is Grigg-Skjellerup [47]. A listing of comet flight opportunities has been prepared [48]. The aspect of multiplicity of targets in flyby has been investigated [11, 49, 50, 51]. The choice of target combination in early ballistic missions is largely a question of the timing of the earliest realistic opportunity for a combined comet-asteroid flyby mission. The application of solar electric propulsion (SEP) would greatly enhance the potential of comet-asteroid exploration and make it possible to select flyby sequences of targets selected on the basis of their presumed or observed differences. It would also open the possibility for rendezvous missions.

In the case of cometary rendezvous missions, decisive considerations will arise from the information on the state of the cometary interior obtained in the first flyby missions, and furthermore, on accessibility and technological readiness.

In the case of the asteroids, the early flyby selection would be determined by scientific considerations and accessibility and economy (points 1 and 2) which for the scientific reasons outlined above specifically favor the asteroid Eros [52]. In combination with cometary exploration, technological considerations (point 3) also becomes of interest.

For the first rendezvous and landing missions to asteroids, again the combination of all the arguments involved point to the near-Earth asteroids, with minimal eccentricity such as Eros, as the prime targets.

B. Terrestrial and Lunar Lagrangian Clouds and Trojan Asteroids

The experience of operation in a particle-rich environment gained in exploration of the cometary interior should be applied to investigation of the material accumulated in the Lagrangian points L_4 and L_5 of Jupiter, including the Trojan asteroids. This may represent gravitational focused remainders of the original Jovian jet stream. Under these circumstances, this material would provide the only accessible information on the composition of the earthy and icy components of Jupiter and on the early phases of the accretion of this giant planet. Thus, missions to the Trojans would be a most important step in the outer planet exploration program.

C. Main Belt Asteroids and Satellites

At the time when experience has been gained through asteroid exploration in the near Earth environment, exploration by rendezvous and landing should be extended to other objects of particular scientific interest in the main asteroid belt. When properties of asteroids have been explored from several rendezvous and landing missions, the Martian satellites would constitute important subsequent objects of investigation. They are of interest because they are similar to asteroids from the point of view of size and related properties, but probably represent another mode of the heterogenic process (namely the emplacement and aggregation of matter around a planet). For the same reason, exploration of the regular satellite system of Jupiter would constitute a logical extension for the future, although more distant in terms of accessibility and economy (point 2).

D. Time Sequence of Exploration⁴

A possible program that would take into account the priorities as specified would combine the following aspects:

1. Intensified observations from Earth of the high-priority targets for early asteroid and comet missions will provide important new information, influencing the design of experiments and the technical approach. Such ground based studies should, for this reason, be initiated as soon as possible by

4. Adopted from the preliminary deliberations of the NASA Comet-Asteroid Working Group.

financing of a ground based facility dedicated to this purpose, and by encouragement of national and international activities in this field.

2. 1976 flyby of Comet Grigg-Skjellerup
3. 1980 Helios C flyby of Comet Encke
4. Multiple slow flyby of a series of near-Earth asteroids (Amor and Apollo group), using solar electric propulsion
5. 1984 rendezvous with Comet Encke
6. Rendezvous missions exploring near-Earth asteroids in 1984
7. 1986 flyby or rendezvous missions to Comet Halley
8. Extended rendezvous exploration of selected main belt asteroids and other objects of special interest such as the Trojans
9. Mid-1980's landing missions with roving vehicles and sample return from near-Earth asteroids
10. Sample return from the interior of comets

REFERENCES

1. Alfvén, H. ; and Arrhenius, G. : Structure and Evolutionary History of the Solar System, I. Astrophysics Space Science, vol. 8, 1970, pp. 338-421.
2. Alfvén, H. ; and Arrhenius, G. : Origin and Evolution of the Solar System, II. Astrophysics Space Science, vol. 9, 1970, pp. 3-33.
3. Gehrels, T., ed. : Physical Studies of Minor Planets. Proc. 12th Coll. IAU, NASA SP-267, GPO, Washington, D.C., 1971.
4. Lyttleton, R. A. : Does a Continuous Solid Nucleus Exist in Comets ? Astrophysics Space Science, vol. 15, 1972, p. 175.
5. Stein, W. : Circumstellar Infrared Emission. Presented at Astronomical Society of Pacific Symposium, Santa Cruz, Cal., June 26-29, 1972.
6. Alfvén, H. : On Formation of Celestial Bodies. Icarus, vol. 3, 1964, p. 57.
7. Hartmann, W. K. ; and Larson, S. M. : Angular Momenta of Planetary Bodies. Icarus, vol. 7, 1967, pp. 257-260.
8. Guili, R. T. : On the Rotation of the Earth Produced by Gravitational Accretion of Particles. Icarus, vol. 8, 1968, pp. 301-323.
9. Van Houten-Groeneveld, I. : Personal Communications. 1972.
10. Taylor, R. C. : Photometric Observations and Reductions of Light-curves of Asteroids. Physical Studies of Minor Planets, Proceedings 12th Coll. IAU, NASA SP-267, T. Gehrels, ed., 1971, pp. 117-131.
11. Bourke, R. D. ; and Friedlander, A. L. : Potential Flight Missions for Comets and Asteroids. Washington, D.C.
12. NASA Comet-Asteroid Mission Study Panel: Comets and Asteroids, A Strategy for Exploration, NASA TM X-64677, 1972.

REFERENCES (Continued)

13. Danielsson, L; and Ip, W. H.: On the Existence of a Resonance-Captured "Quasi-Satellite" of the Earth. From Plasma to Planet, Proceedings of Nobel Symposium, vol. 21, A. Elvius, ed., Wiley, New York, 1971, pp. 354-358.
14. Danielsson, L.; and Ip, W. H.: Capture Resonance of the Asteroid 1685 Toro by the Earth. Science, vol. 176, 1972, pp. 906-907.
15. Ip, W. H.; and Mehra, R.: Resonances and Liberation of Some Apollo and Amor Asteroids. Astron. J., 1972.
16. Alfvén, H.; and Arrhenius, G.: Origin and Evolution of the Earth-Moon System. The Moon, vol. 5, 1972, pp. 210-230.
17. Chapman, R. C.: Surface Properties of Asteroids. Doctorial Dissertation, MIT, 1972.
18. Mendis, D. A.: The Comet-Meteor Stream Complex. Astrophysics Space Science, 1973.
19. Trulson, J.: Proceedings of IAU Symposium No. 45, Leningrad, 1970.
20. Delsemme, A. H.: Nature and Origin of Cometary Heads. Comets Scientific Data Missions, Proceeding of Tucson Comet Conference, G. P. Kuiper and E. Roemer, eds., 1972, pp. 32-47.
21. Lal, D.: Space Irradiation of Solids. From Plasma to Planet, Proceedings of Nobel Symposium, vol. 21, A. Elvius, ed., Wiley, New York, 1971.
22. Maas, R. W.; Ney, E. P.; and Woolf, N. J.: The 10-Micron Emission Peak of Comet Bennett 1969. Astrophysic Journal Letters, vol. 160, 1970, Letter 101.
23. Schubart, J.: Asteroid Masses and Densities. Physical Studies of Minor Planets, Proceedings of 12th Coll. IAU, NASA SP-267, T. Gehrels, ed., 1971, pp. 33-39.

REFERENCES (Continued)

24. Forward, R. L.: Asteroid Mass Distribution Measurement with Gravity Gradiometers. *Physical Studies of Minor Planets, Proceeding of 12th Coll. IAU*, NASA SP-267, T. Gehrels, ed., 1971, pp. 585-593.
25. Alfvén, H.: Spacecraft Propulsion: New Methods. *Science*, vol. 176, 1972, pp. 167-168.
26. Asunmaa, S. K.; Liang, S. S.; and Arrhenius, G.: Primordial Accretion; Inferences from the Lunar Surface. *Proceeding of Apollo II Lunar Science Conference*, vol. 1, Pergamon Press, 1970, pp. 1975-1985.
27. Asunmaa, S. K.; and Arrhenius, G.: Electrostatic Interparticle Adhesion in Apollo 15 Fines. *The Apollo 15 Lunar Sample*, J. W. Chamberlain and C. Watkins, eds., Lunar Science Institute, Houston, Texas, 1972.
28. Yerkes Observatory: Proceedings of the Cometary Science Working Group, C. R. O'Dell Ch., D. L. Roberts, ed., ITT Research Institute, 1971.
29. Annan, A. P.: Radio Interferometry Depth Sounding, Part I- Theoretical Discussion. *Geophysics*, 1972.
30. Chung, D. H.; and Westphal, W. B.: Dielectric Properties of Apollo 14 Lunar Samples. *Lunar Science III*, C. Watkins, ed. Lunar Science Institute, Houston, Texas, Contribution 88, 1972.
31. Rossiter, J. R.; LaTorraco, G. A.; Annan, A.; Strangway, D. W.; and Simmons, G.: Radio Interferometry Depth Sounding, Part II- Experimental Results. *Geophysics*, 1972.
32. Anders, E.: Conditions in the Early Solar System, as Inferred from Meteorites. *From Plasma to Planet, Proceeding of Nobel Symposium*, vol. 21, A. Elvius, ed., Wiley, New York, 1971, pp. 133-156.
33. Adler, I.; Trombka, J. I.; and Gorenstein, P.: Remote Chemical Analysis During the Apollo 15 Mission. *Anal. Chem.*, vol. 44, 1972, pp. 28a-35a.

REFERENCES (Continued)

34. Metzgen, A. E.; Trombka, J. I.; Peterson, L. E.; Reedy, R. C.; and Arnold, J. R.: Lunar Surface Radioactivity: Preliminary Results of the Apollo 15 and 16 Gamma Ray Spectrometer Experiments. *Science* 1972.
35. Wittry, D.; Arrhenius, G.; and Cohen, L.; Determination of Surface Composition of the Moon from a Lunar Satellite. *Geofis. International*, vol. 1, 1965, pp. 95-106.
36. Jacklevic, J. M.; and Goulding, F. S.; Detection of Low Energy X-Rays with Si(Li) Detectors. *IEEE Trans. Nucl. Sci.*, 1970.
37. Turkevich, A. L.: Comparison of the Analytical Results from the Surveyor, Apollo, and Luna Missions. *Proceedings of 2nd Lunar Science Conference*, vol. 2, The MIT Press, 1971, pp. 1209-1215.
38. Fitzgerald, R. W.; and Gantzel, P.: X-Ray Energy Spectrometry in the 0.1 to 10A Range. *Special Technical Publication 485*, ASTM, Philadelphia, 1971, pp. 3-35.
39. Clark, B. C.: X-Ray Surface Sample Analyzer for Planetary Exploration. *Final Report, NASA Contract NASW-2248*, 1972.
40. Arrhenius, G.; and Alfvén, H.: Asteroidal Theories and Experiments. *Physical Studies of Minor Planets. Proceedings of 12th Coll. IAU*, NASA SP-267, T. Gehrels, ed., 1971, pp. 213-223.
41. Arrhenius, G.: Chemical Effects in Plasma Condensations. *From Plasma to Planet, Proceedings of Nobel Symposium*, vol. 21, A. Elvins, ed., Wiley, New York, 1971, pp. 117-132.
42. Arrhenius, G.; and Alfvén, H.: Fractionation and Condensation in Space. *Earth Planet Sci. Letters*, vol. 10, pp. 253-267.
43. Ohman, Y.: The Asteroids as Possible Research Objects for Future ESRO Missions. *Copers LPSC 89*, European Preparatory Commission for Space Research Landing, 1963.
44. Walter, J.: Private Communication. ORTEC Inc., Oak Ridge, Tennessee, 1972.

REFERENCES (Concluded)

45. Gregory, J. C.; and Parnell, T. A.: A Low Power X-Ray Diffractometer for Soil Analysis in Remote Locations Employing a Multiwire Proportional Counter Detector Array. Proceeding of Nuclear Science Symposium.
46. Lindblad, B. A.; A Stream Search Among 865 Precise Photographic Meteor Orbits. Smithsonian Contributions to Astrophysics, 1970.
47. Ness, N.; Burlaga, L.; Farguhar, R.; Donn, B.; Jackson, W.; and McCarthy, D.: Cometary Explorer to Grigg-Skjellerup, 1977. GSFC, N72-32850, X-690-72-337, 1972.
48. Northrop Services, Inc.: A Catalog of Comet and Asteroid Mission Opportunities and Characteristics. Northrop Services TR-250-1099, NASA Contract NAS8-28427, Second Preliminary Edition, 1972.
49. Bender, D. F.; Asteroid Encounters on Grand Tour and Other Missions Which Traverse the Region Beyond Mars. Astrodynamics Specialist Conference, Ft. Lauderdale, Florida, August, 1971.
50. Friedlander, A.: Multiple-Comet Flyby Opportunities. Unpublished Memorandum, November, 1971.
51. TRW Systems Group: Study of Multiple Asteroid Flyby Missions. Mid-Term Review, NASA Contract NAS2-6866, 1972.
52. Moore, J. W.; Bejczy, A.; Phen, R.; Atkins, K.; Bender, D.; Roberts, P.; and Sawyer, C.: A Mission Analysis Study of Comet Rendezvous and Asteroid Docking. Jet Propulsion Laboratory 760-71, Pasadena, Calif., 1972.

BIBLIOGRAPHY

Alfvén, H.: Partial Corotations of a Magnetized Plasma. *Icarus* 7, pp. 387-393.

Alfvén, H.; and Arrhenius, G.: Arguments for a Mission to an Asteroid. *Physical Studies of Minor Planets, Proceedings of 12th Coll, IAU, NASA SP-267*, Edited by T. Gehrels, 1971.

Frazer, J. Z.; Frijita, H.; and Fitzgerald, R. W.: A New Procedure for Quantitative X-Ray Analysis with Electron Excitation. *Mat. Res. Bull. No. 6*, 1971, pp. 711-724.

Kuiper, G. P.; and Roemer, E., Eds.: *Comets Scientific Data and Missions. Proceedings of Tucson Comet Conference, Tucson, Arizona, July, 1972.*

NASA, Ames Research Center: *Pioneer Asteroid and Comet Flyby Mission Preliminary Analysis*. November, 1971.

NASA, Langley Research Center: *An Evaluation of Technology Needed for Space Environment Investigations. Spart Study*, 1972.

Northrop Services, Inc.: *A Feasibility Study of Unmanned Comet and Asteroid Rendezvous and Docking Concepts Using Solar Electric Propulsion*. Sp-250-1003, 1971.

Reedy, R. C.; and Arnold, J. R.: Interaction of Solar and Galactic Cosmic-Ray Particles with the Moon. *Journal of Geophysics, Res.* 77, 1972, pp. 537-555.

Roach, F. E.; and Roach, J. R.: *A Photometric Perturbation of the Gegenschein*. Preprint, 1972.

Roach, F. E.; Carroll, B.; Roach, J. R.; and Aller, L. R.: *A Photometric Study of the Gegenschein from Space*, Preprint, 1972.

TRW, Inc.: *Study of a Solar Electric Multi-Mission Spacecraft. Final Summary Technical Report (Revised)*, TRW Document 09451-6001-RO-03, 1970.

BIBLIOGRAPHY (Concluded)

TRW Systems Group: Study of a Comet Rendezvous Mission. Volume 1, Technical Proposal, RFP No. GQ-1-2696-77.

TRW Systems Group: Comet Encke Rendezvous Preliminary Mission Plan and Questionnaire.



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